PD76-0200
CONTRACT NAS8-31370

(NASA-CR-150223) INVESTIGATION OF LIGHTWEIGHT DESIGNS AND MATERIALS FOR LO2 AND LH2 PROPELLANT TANKS FOR SPACE VEHICLES, PHASE 2 AND PHASE 3 Final Report (General Dynamics/Convair) 226 p HC A11/MF A01 G3/18

N77-20156

Unclas
22836

INVESTIGATION OF LIGHTWEIGHT DESIGNS AND MATERIALS FOR LO_2 AND LH_2 PROPELLANT TANKS FOR SPACE VEHICLES

FINAL REPORT FOR PHASE II (DESIGN) AND PHASE III (MANUFACTURING)

GENERAL DYNAMICS
Convair Division

PD76-0200

INVESTIGATION OF LIGHTWEIGHT DESIGNS AND MATERIALS FOR LO_2 AND LH_2 PROPELLANT TANKS FOR SPACE VEHICLES

FINAL REPORT FOR PHASE II AND PHASE III

December 1976

Prepared for
National Aeronautics and Space Administration
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama
Prepared Under
Contract NAS 8-31370

Prepared by
GENERAL DYNAMICS CONVAIR DIVISION
P.O. Box 80847
San Diego, California 92138

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Concld)

LIST OF TABLES

INTRODUCTION

The purpose of this study was to investigate lightweight designs and materials for LO_2 and LH_2 propellant tanks to be used on space vehicles such as the Space Tug. Various tankage concepts and materials were considered in combinations such that a complete tank design could be selected for fabrication and testing. The selected design provided proper strength characteristics with minimum total system weight. Design considerations included safety, reliability, and multiple reusability under combined cryogenic and Space Shuttle environments.

These design, analysis, and fabrication studies were performed on nonintegral (suspended) tanks using a representative Space Tug design as outlined in MSFC Report No. 68M0039-2, Baseline Space Tug, Configuration Definition.

The LH_2 and LO_2 tank concept selection was developed in Phase I. Tank geometries and support relationships were investigated using Tug design propellant inertias and ullage pressures, then compared based on total Tug systems effects. The tank combinations which resulted in the maximum payload were selected. Tests were conducted on samples of membrane material which was processed in a manner simulating production tank fabrication operations to determine fabrication effects on the fracture toughness of the tank material. Fracture mechanics analyses were also performed to establish a preliminary set of allowables for initial defects. The results of this study Phase were documented in the Interim Report PD75-0117.

This final report covers the results of Phase II and III design, analysis, and manufacturing. Full size Tug LO_2 and LH_2 tank configurations were defined, based on the Phase I selected tank geometries. These configurations were then locally modeled for computer stress analysis. A large subscale test tank, representing the selected Tug LO_2 tank, was designed and analyzed. This tank was fabricated using procedures which represented production operations. An evaluation test program was outlined and a test procedure defined. The necessary test hardware was also fabricated.

1

PRELIMINARY DESIGNS

The objectives of this task were:

a. Expand basic selected Phase I tank concept into preliminary design layouts.

b. Develop detailed preliminary design drawings including critical tank joints, access provisions, and interface requirements.

c. Specify critical internal joints, gages, stiffeners, and external tank interfaces.

d. Size all tank elements.

The Tug tankage detail design requirements were assembled into a single document (see Appendix A). Then detailed tank configurations were developed, based on this document, using the contours and optimum support arrangements defined in Phase I.

1.1 LH_2 TANK PRELIMINARY DESIGN

The complete LH_2 predesign configuration is shown in Figure 1-1. The general configuration is as selected in Phase I; i.e., two Cassinian bulkheads ($n = 1.879$) with a 40.56-cm (15.97 in.) cylindrical section. The tank characteristics are:

a. Working pressure, 11.6 N/cm^2

b. Volume, 49.50 m^3

c. Material, 2219T87 Aluminum Alloy

The tank skin is chemically milled equally from both surfaces to maintain the membrane neutral axis centered through all transition steps. The basic shell fabrication procedure is to form the contour in the 2219-T37 condition, age to 2219-T87, chemical mill to the prescribed pattern, and then butt-weld the gores together. The outlet and door ring would be welded into the cap pieces prior to welding the caps to the gore subassembly. The primary features developed during Phase II are the siamese gore approach (no girth weld), 3.048-m (120 in.) diameter cap pieces and localized support bracket membrane footprints. The access door design (section M-M) and the pass-thru (detail-P) incorporate cono-seal gaskets for minimum leakage. The primary support brackets (View J-J) are a single-blade design with an integral rod end bearing. Therefore, the attaching strut will have a clevis fitting. An alternate tank-mounting clevis fitting is shown for strut concepts which are rod end fittings. Internal brackets are provided for support of the vent line and the vortex baffles. The anti-pull-through plate is a weldment with vanes, welded to the tank wall. Provisions are shown for the

pressurization bubbler manifold on top of the vortex baffles. A typical pass-thru cluster for pneumatic lines is also defined in Section X-X of the drawing.

The local membrane buildup and bracket design is detailed for the forward-mounted side-load struts (View D-D). This design is similar to the main support system concept (i.e., single blade bracket). The main door design is a flush-mount concept. The tank contour lines are shown separately in Figure 1-2. These offset dimensions were reviewed for producibility based on material elongation. The gore widths and cap diameter were selected based on a maximum of six percent elongation.

1.2 LO_2 TANK PRELIMINARY DESIGN

The complete LO_2 tank predesign configuration is shown in Figure 1-3. The general configuration is as selected in Phase I, i.e., two ellipsoidal bulkhead (a/b = 2) with a 3.66-m (144 in.) major diameter. The primary features developed during Phase II are the siamese gore approach (no girth weld), 2.54-m (100 in.) diameter cap pieces, localized support bracket membrane footprints, and integral rib (frame) support for lateral load effects. The access door design and large pass-thrus incorporate cono-seal gaskets and the small pneumatic pass-thrus are all-welded to ensure minimum leakage. The primary support brackets are single-blade design with an integral rod end bearing. These brackets are shown fillet welded to the tank membrane.

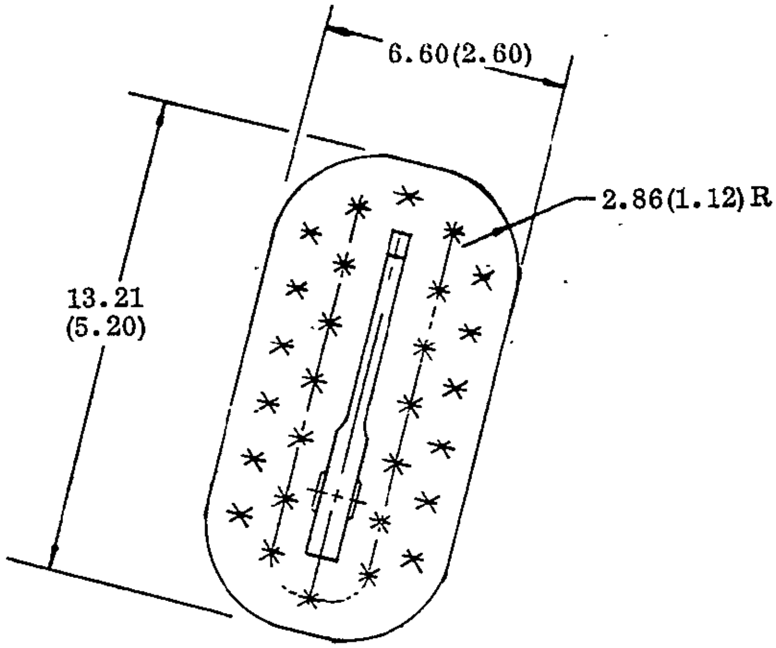
Additional study was performed to evaluate other methods of attaching brackets to the lightweight tank. The predesign bracket attachment concepts were based on fillet welding blades or clevis-type fittings to raised shell pads. This type of bracket attachment was used in several areas on the three 2219 aluminum tanks designed and fabricated for the NASA Lewis Research Center. Table 1-1 is a list of all of the fillet welded parts fabricated and a tabulation of the lengths of welds. Two additional candidates for attaching brackets to thin aluminum shells are spot welding and weld bonding. (See Figure 1-4.) Brackets are presently attached to the Centaur vehicle shell by spot welds, whereas weld bonding is providing to be a reliable method of using adhesive to transfer loads in shell type structures. Brackets for these three concepts have been sized for the LO_2 predesign tank supports and their weights calculated (without bearings). The results are shown in Table 1-2. The fillet weld method results in the lightest configuration.

The anti-pull-thru plate is a weldment with vanes welded to the door. The main engine feed outlet is in the center of the door.

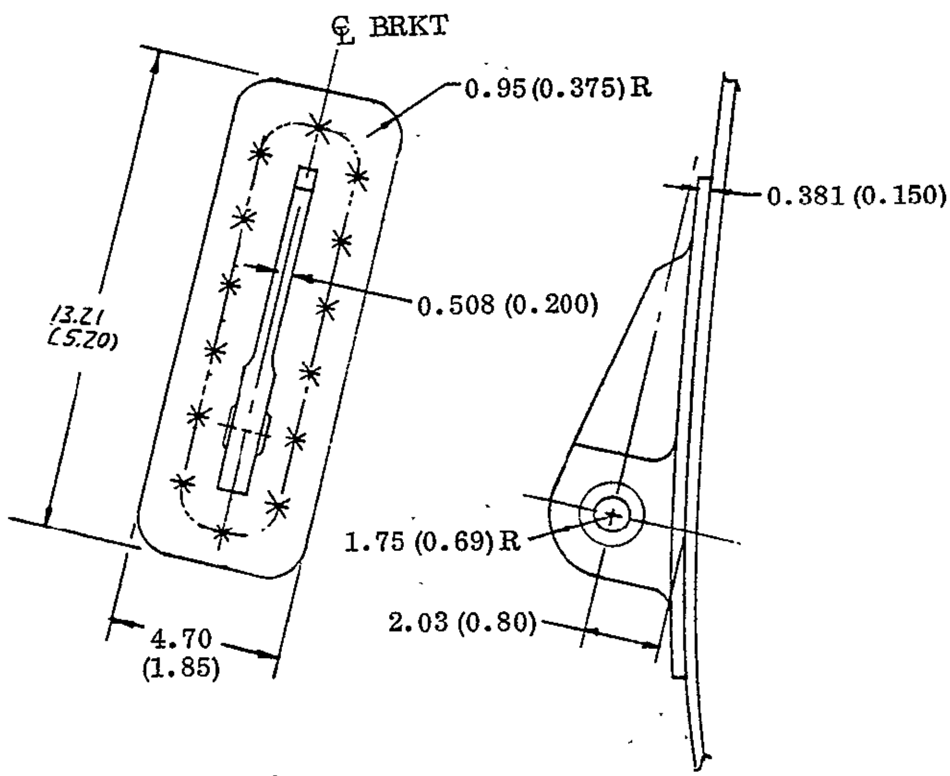
The engine is mounted directly to the door through a welded thrust cone configuration, allowing the thrust loads to be reacted by LO_2 tank pressure at the door ring diameter.

Table 1-1. Fillet welds.

Item	Part No.	Quantity	Weld Length (cm)	Weld Length (in.)	Material
Methane Tank	PD70-0129	—	548.6	216	2219 AL ALY (0.41 cm (0.160 in.) @ welds)
- Bracket	PD70-0134-2	2	30.5	12.0	0.41 cm (0.16 in.) 2219T852
- Clip	PD70-0133-1	8	5.1	2.0	0.203 cm (0.080 in.) 2219T0
- Baffle	PD70-0132-1	1	20.3	8.0	0.203 cm (0.080 in.) 2219T42
- Bracket	PD70-0130	6	71.1	28.0	0.397 cm (5/32 in.) 2219T852
LO_2 Tank	PD70-0108	—	619.8	244	2219 AL ALY (0.394 cm (0.155 in.) @ welds)
- Bracket	PD70-0109-1	6	76.2	30.0	0.508 cm (0.200 in.) * 2219T852
- Clip	PD70-0116-1	2	7.6	3.0	0.317 cm (0.125 in.) 2219T852
- Bracket	PD70-0113-2	1	33.0	13.0	0.356 cm (0.140 in.) 2219T852
- Bracket	PD70-0113-1	1	33.0	13.0	0.356 cm (0.140 in.) 2219T852
- Clip	PD70-0112-1	12	5.1	2.0	0.317 cm (0.125 in.) 2219T0
- Baffle	PD70-0111-1	1	20.3	8.0	0.203 cm (0.080 in.) 2219T42
					* Weld Leg.
Flox Tank	PD70-0147	—	673.1	265	2219 AL ALY (0.635 cm (0.250 in.) @ welds)
- Clip	PD70-0156-1	12	5.1	2.0	0.203 cm (0.080 in.) 2219T0
- Baffle	PD70-0155-2	12	3.5	1.38	0.305 cm (0.12 in.) 2219T42
- Baffle	PD70-0155-1	12	2.5	1.0	0.305 cm (0.12 in.) 2219T42
- Baffle	PD70-0150-1	1	20.3	8.0	0.317 cm (0.125 in.) 2219T42
- Bracket	PD70-0148-1	6	86.4	34.0	0.397 cm (5/32 in.) 2219T852



BASED SIZED FOR
SPOT WELDS ONLY



WELD BOND
CONFIGURATION

Figure 1-4. Alternate bracket attachment methods.

Table 1-2. Bracket study, lightweight tank.

Parameter	Design: Fillet Weld	Spot Weld	Weld Bond (EC2214)
Weight for 24 (w/o Bearing)	1.96 kg (4.32 lb)	3.26 kg (7.20 lb)	2.61 kg (5.76 lb)
Load Transfer Consideration	Length of Weld and Depth	Number of Spots	Surface Area
M.S. (ult)	0.48	0.19	0.03

The general thrust structure layout (Figure 1-5) was a special layout developed to determine the feasibility of the engine attachment and feed line routing required for a dry cone structure attachment directly to the aft LO_2 bulkhead. The layout indicates that this approach is realistic. An integral shell stiffening pattern is shown around the door ring. This design was developed for evaluation in Phase I. With this shell stabilization the engine would not require external support during transportation.

Table 1-3 presents LO_2 and LH_2 tank weight statements.

Table 1-3. Tank weights.

Oxidizer Tank, Lightweight Design (Ellipse)		Hydrogen Tank, Lightweight Design (Cassinian Bulkhead)	
Total Weight	255.8 lb (116.0 kg)	Total Weight	359.3 lb (163.0 kg)
Shell		Shell	
Fwd Bulkhead	67.4	Fwd Bulkhead	131.4
Aft Bulkhead	93.9	Cylinder	32.3
Stiffener Lands	3.8	Aft Bulkhead	118.4
Weld Lands	16.0	Weld Lands	38.6
Support Band	10.3	Vent Line Supports	0.6
Support Fittings	24.6	Reaction Fitting	1.1
Engine Fuel Feed Duct & Support Fittings	0.6	Support Brackets	4.2
Internal Line Supports	0.1	Vent Penetration & Pass Thru Fitting	1.4
Internal Dump Tank Fitting	1.0	Fill Drain & Dump Fittings	2.0
Vent Penetration & Tubular Pass Thru Fitting	1.0	Anti-Rotation Vanes & Baffles	9.2
Misc - Hardware	2.0	Misc - Hardware	1.3
Thrust Cone		Access Door	
Cone	30.1	Door	16.1
Anti-Vortex Plate & Vanes	1.5	Hardware	2.7
Hardware	3.5		

2

ANALYSIS

The objectives of this task were:

a. Perform a preliminary structural analysis of the selected preliminary design concept.

b. Conduct detailed stress analysis on each tank, including: bulkhead membrane sizing, access door, outlet, weld land, thermal effects, baffles, equipment support, and thrust structure.

2.1 SHELL ANALYSIS

Before establishing a firm minimum membrane gage for manufacturing, it was necessary to define the associated weight penalties. These weight penalties were developed for both the LH_2 and LO_2 tanks with respect to the absolute minimum weight of each tank as it would be if all the gages were determined by material tension stress allowables only. Figure 2-1 shows these curves for each tank. The weight penalty can be determined by selecting a minimum gage and reading the associated weight directly from the curve. The zero weight point represents the stress-designed tank. It can be seen that, for a 0.063-cm (0.025-in.) minimum gage, there is only a 10 kg (22 lb) weight penalty in both the LO_2 and LH_2 tanks. A minimum gage of 0.025 was set based on low weight penalty and practical shop handling considerations.

The membrane gage variation in the LH_2 tank bulkheads was determined, using the desk computer program developed in Phase I for shell weights, and the results are plotted in Figures 2-2 and 2-3 for the forward and aft bulkheads, respectively. A 0.063-cm (0.025-in.) minimum gage cutoff line has been drawn on this curve to indicate the areas which require gages greater than this minimum gage. These gages are plotted versus the distance along the bulkhead contour.

The membrane gage variation required in the LO_2 tank due to ullage and inertia head effects has been determined and the results have been plotted as shown in Figures 2-4 and 2-5 for the forward and aft bulkheads, respectively.

The forward bulkhead gages vary smoothly from the girth to the crown, whereas the aft bulkhead has a sharp step at the location of the support tangent point. This is due to the collection of the propellant inertial loads at this point into the support struts. Minimum gages will govern forward of the supports and in the forward bulkhead. Using a 0.063-cm (0.025-in.) minimum gage, the weight penalty is approximately 10 kg primarily due to the forward bulkhead which never requires more than 0.063-cm thickness.

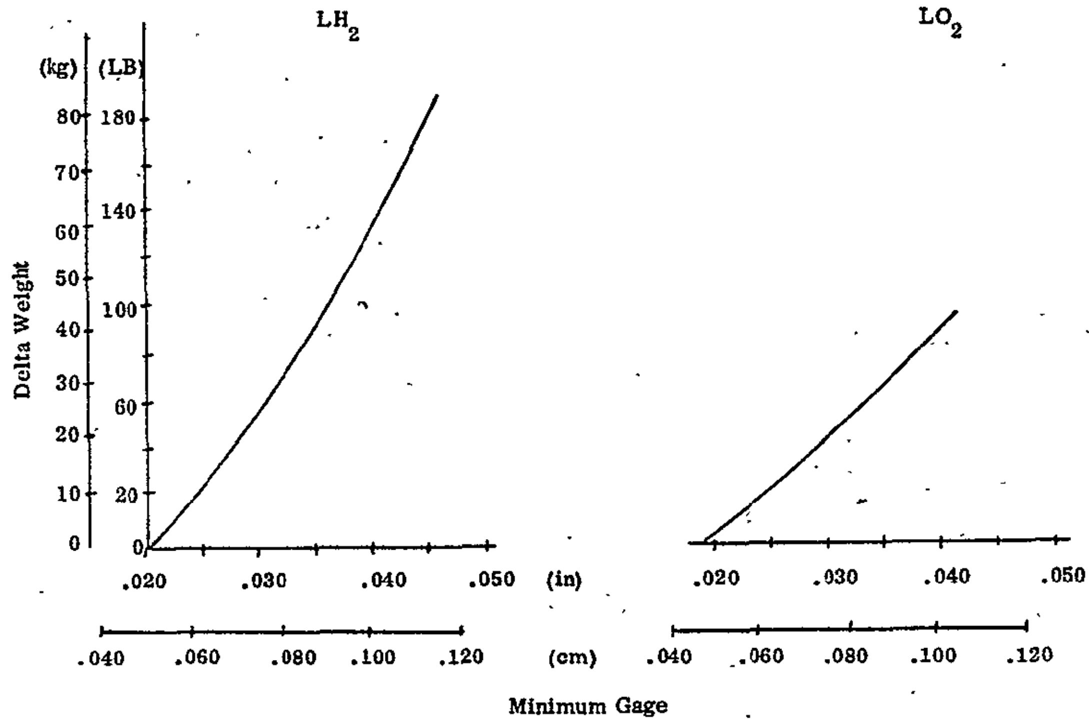


Figure 2-1. Minimum gage weight penalties.

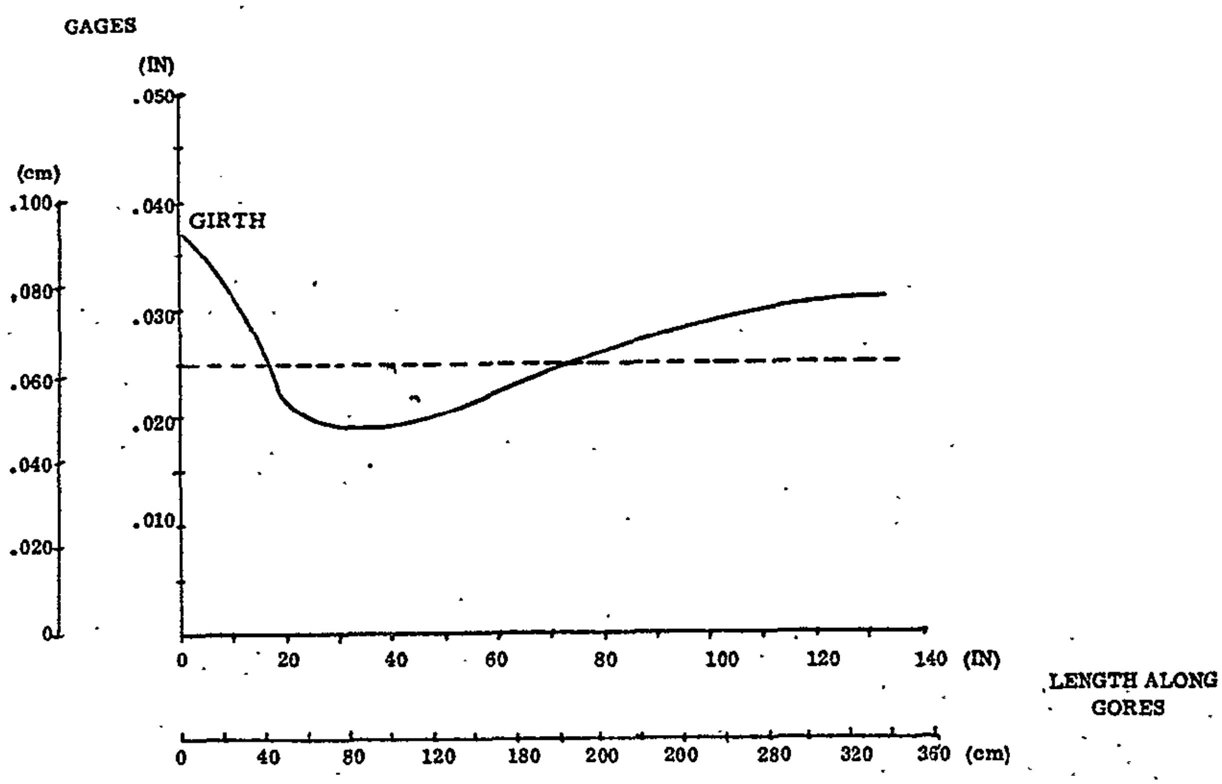


Figure 2-2. LH_2 forward bulkhead gages.

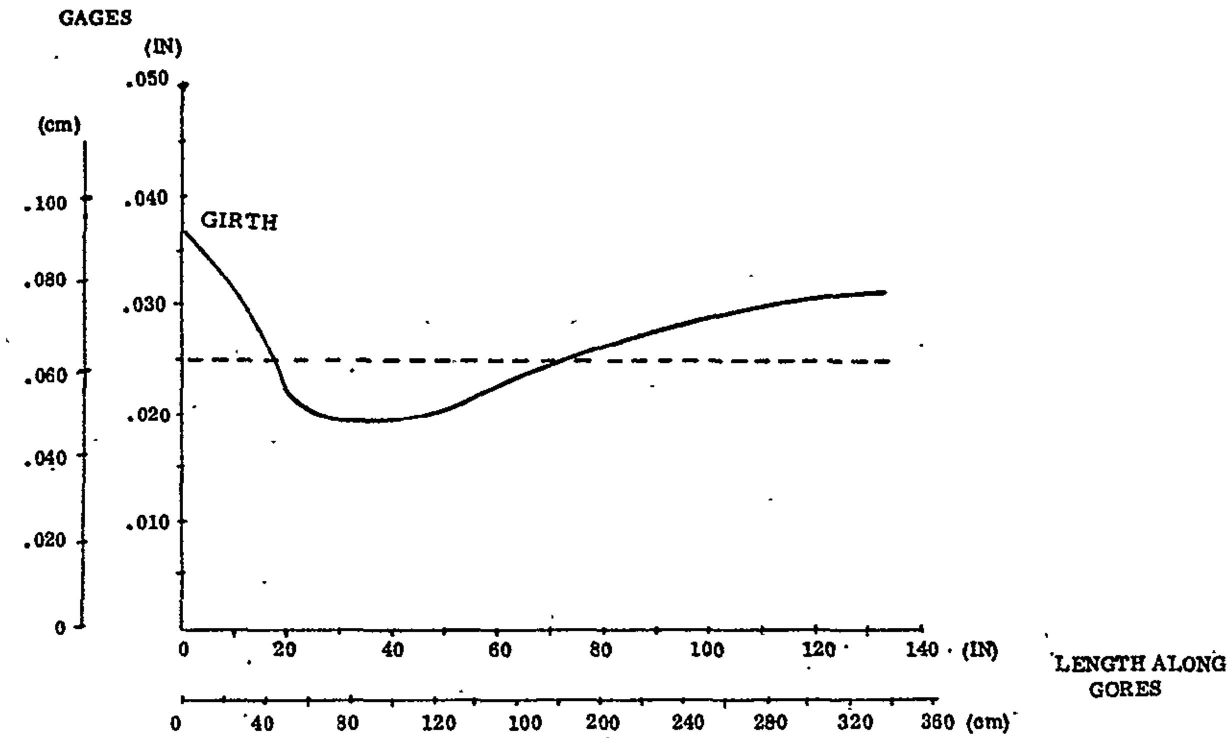


Figure 2-3. LH_2 aft bulkhead gages.

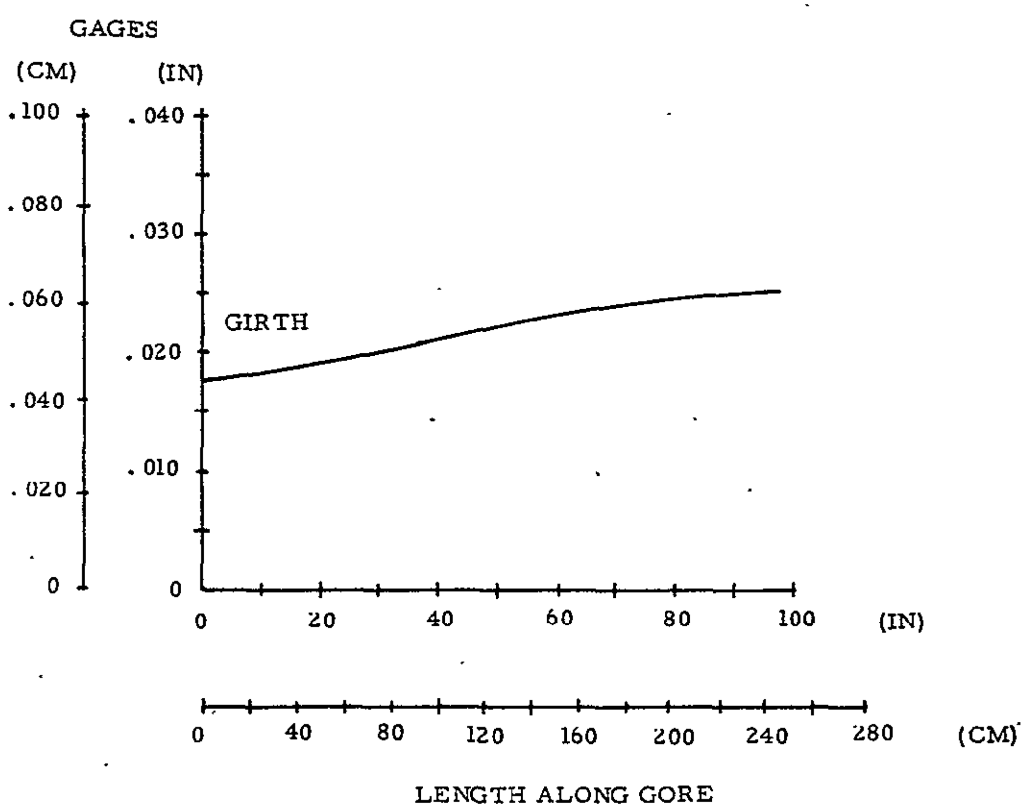


Figure 2-4. LO_2 forward bulkhead gages.

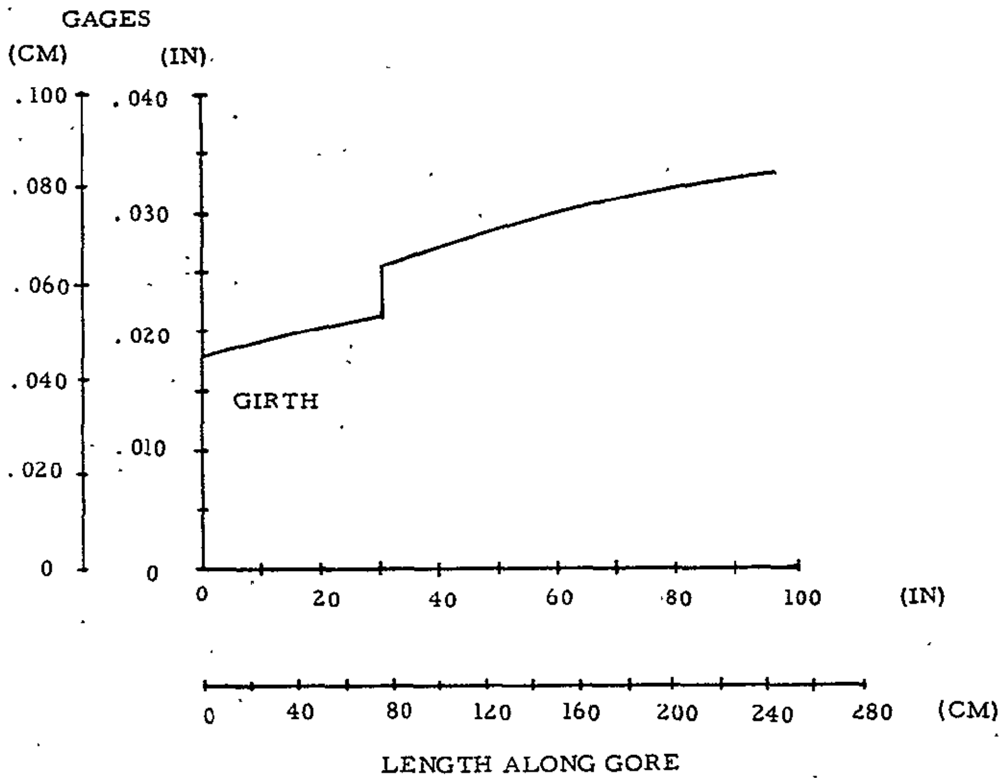


Figure 2-5. LO_2 aft bulkhead gages.

2.2 TANK SUPPORT EFFECTS

The LO_2 tank is supported by twelve sets of support struts located symmetrically around the tank circumference. Because of this symmetry, only 0.26 radian of the total shell structure need be analyzed. This section of shell was modeled using a finite element analysis (Code SAP).

Figure 2-6 is the computer representation of the 0.26-radian shell slice grid. This grid is much finer in the area of the strut attach bracket, to define more clearly the attachment effects. Figure 2-7 shows this support area in more detail as definition to the support bracket band, and Figure 2-8 is a magnification of this area to illustrate the support-bracket-to-shell elements. These figures were produced by a graphics interface with the Cyber 70 computer, thus enabling the analyst to verify the model geometry and element connection. The tank shell thicknesses in the bracket land area was sized using this model, with both ullage and propellant inertial loadings.

The design concept using a circumferential band at the support plane was initially investigated and it was found that the high loop and meridional line loads would cause buckles in this design concept. Figures 2-9 and 2-10 illustrate the membrane hoop compression and meridional compression zones, respectively. It was determined that the circumferential band does not help redistribute the meridional line loads caused by inertial loads. Therefore, this reinforcement away from the attachments is not required

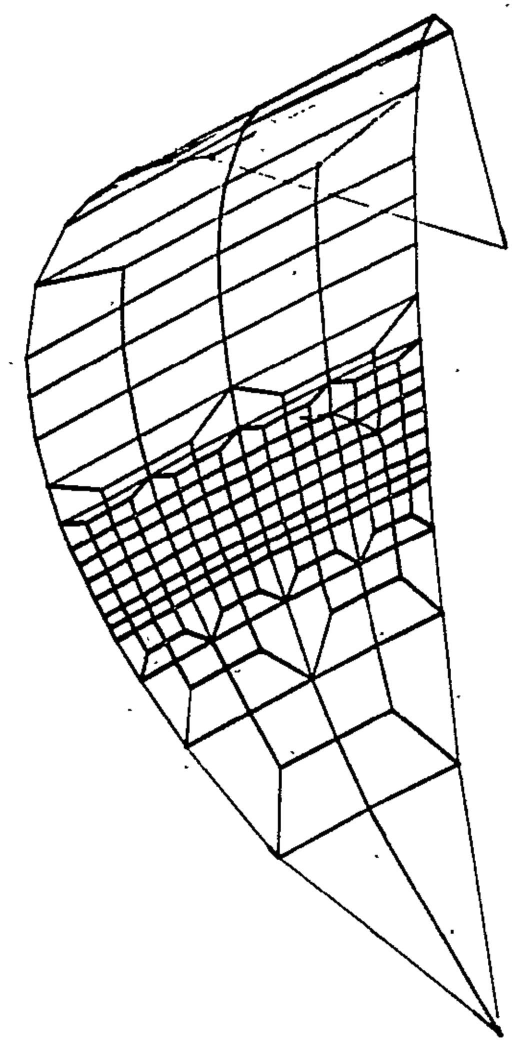


Figure 2-6. Half gore on LO_2 tank.

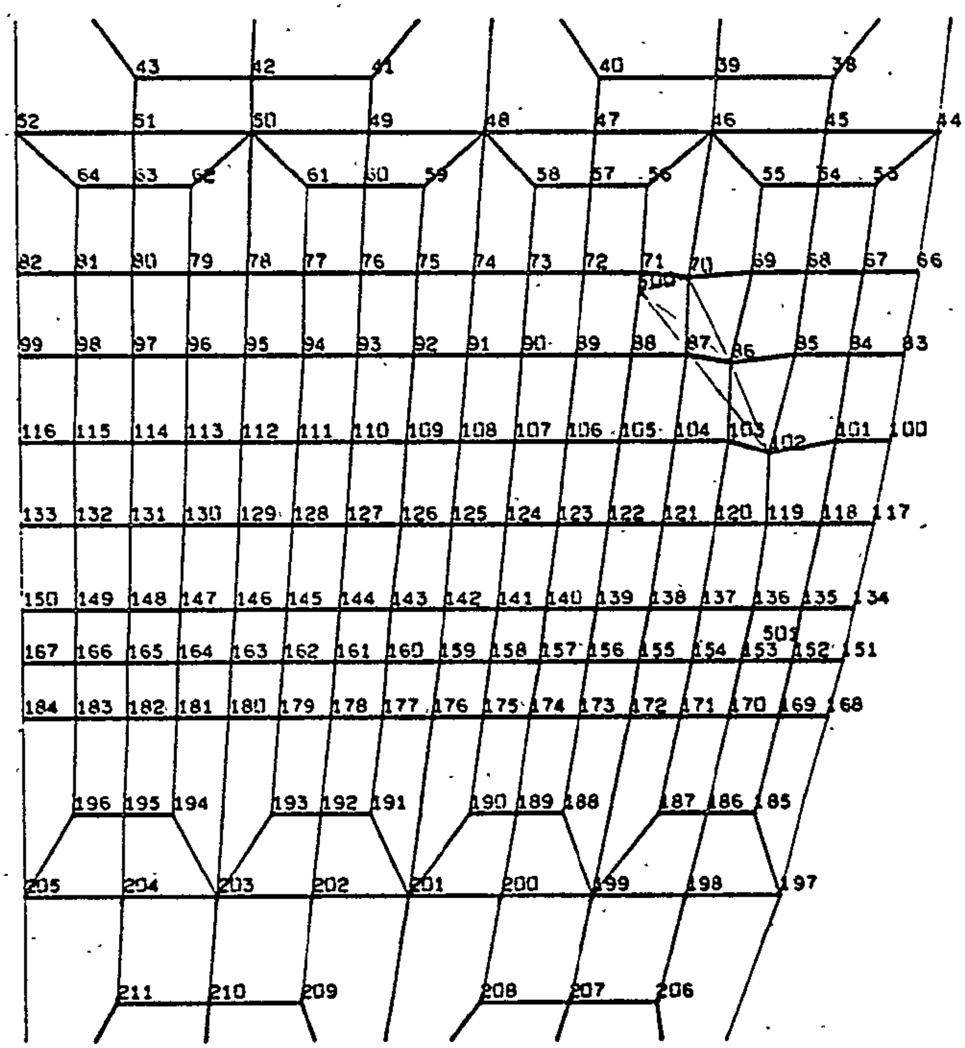


Figure 2-7. Half gore on LO_2 tank (band area).

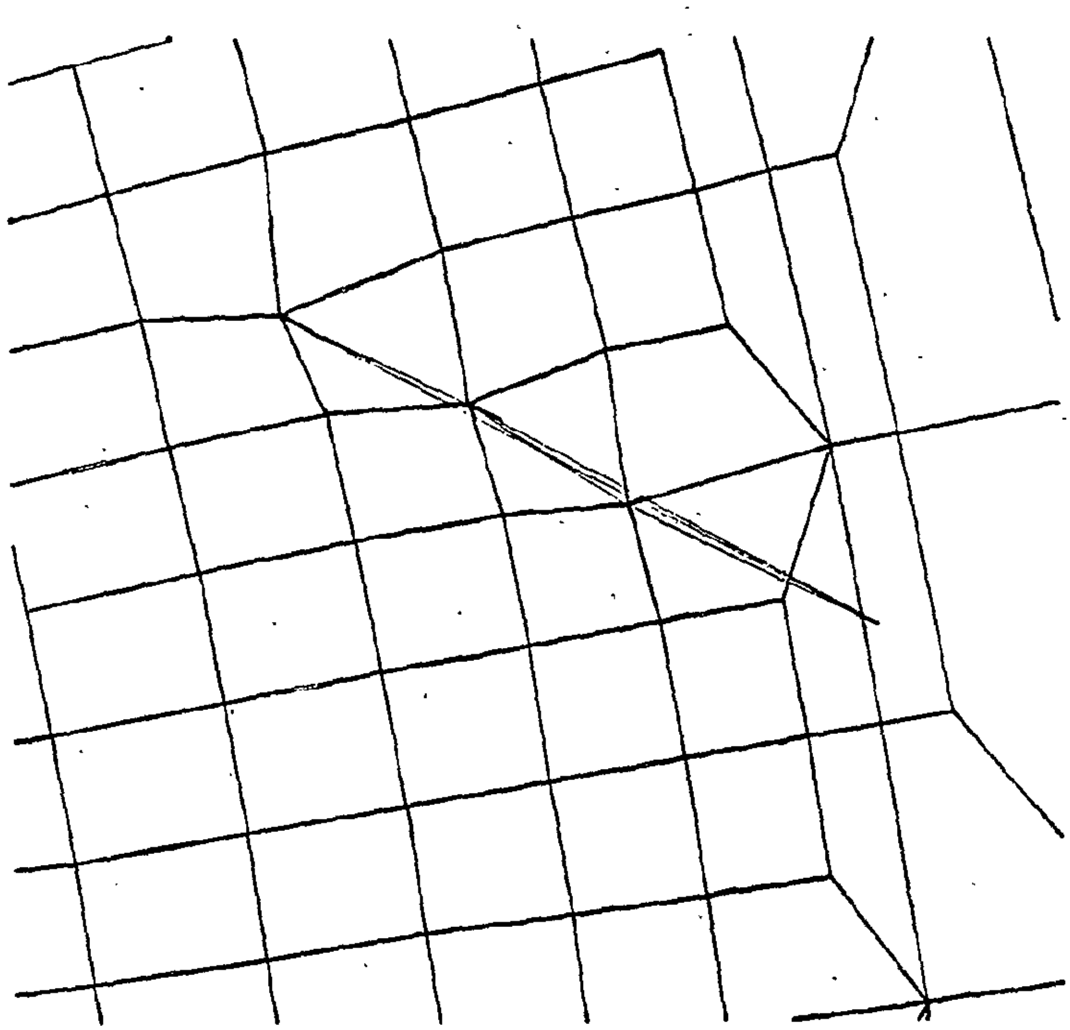


Figure 2-8. Half gore on LO_2 tank (bracket interface).

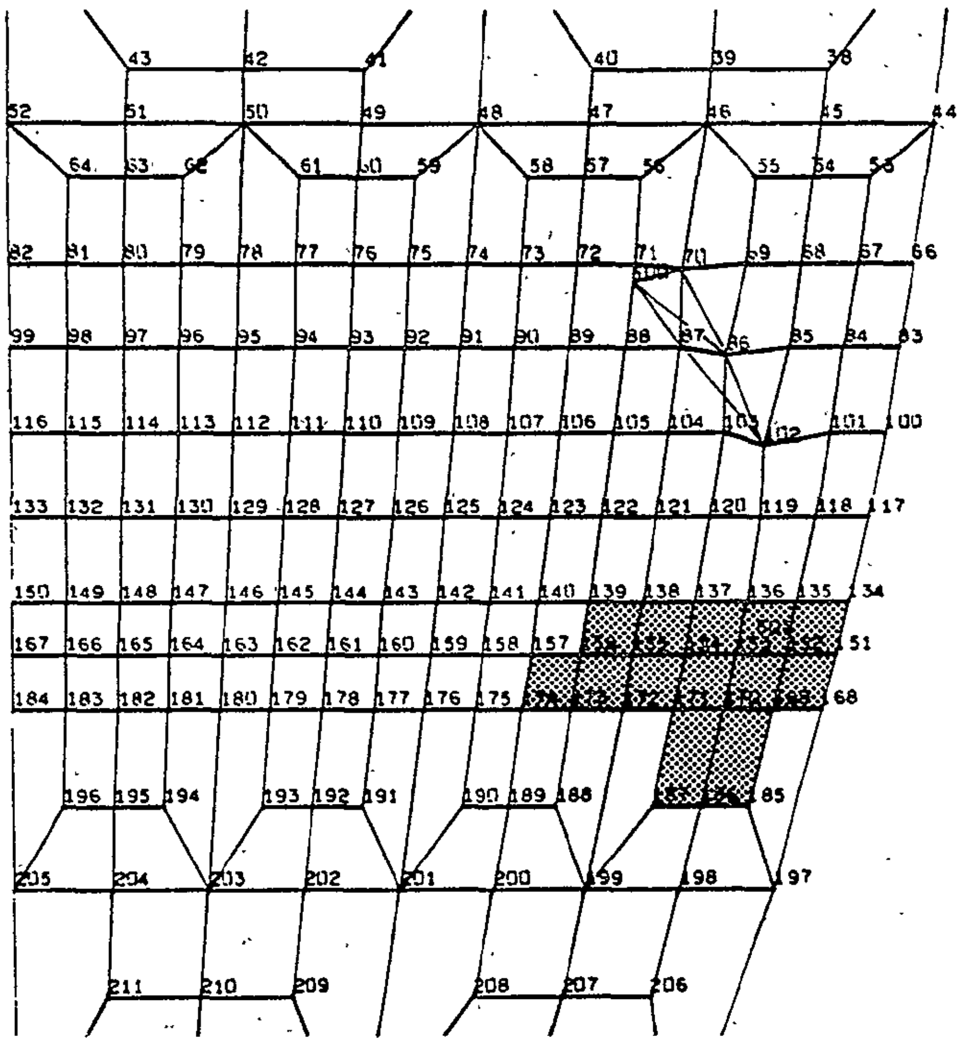


Figure 2-9. Hoop compression zone half gore.

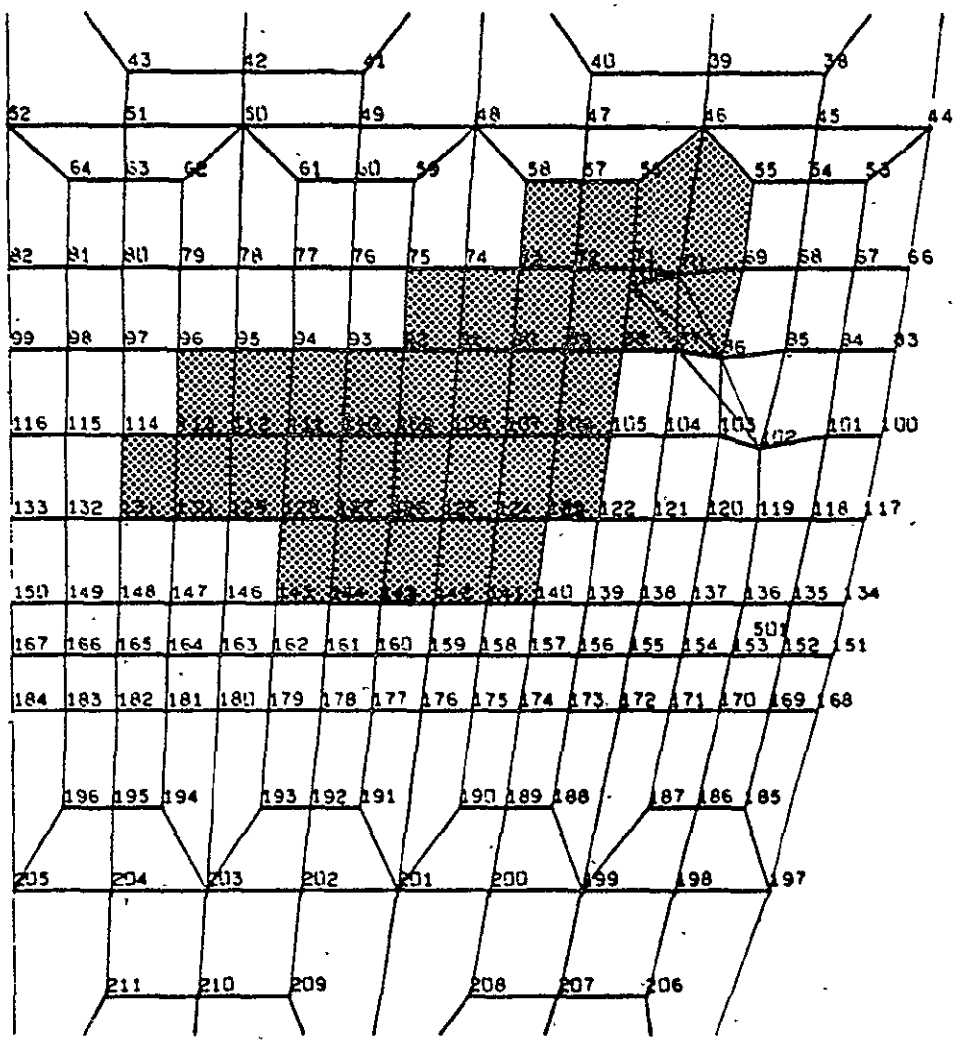


Figure 2-10. Meridional compression zone half gore.

for redistribution. A new attachment foot-print was developed to resist the true shell loading. This local configuration model is shown in Figure 2-11. The finite analysis was run against this configuration. Some high tension stresses in the hoop direction indicate that a circumferential band in the support bracket plane is needed for tension loads. This local band thickness will be 0.1016-cm (0.040-in.) thick. The finite analysis initially was performed in two steps, first to determine the effects of hydrostatic head pressure only, and then with the addition of ullage pressure. With the combined loads there is no net meridional compression in the tank membrane using the local support pad design. The load conditions considered in this analysis were (1) 11.7 N/cm^2 (17 psi) ullage pressure, (2) hydrostatic head with 3.15 g loading, and (3) a combination of the two conditions.

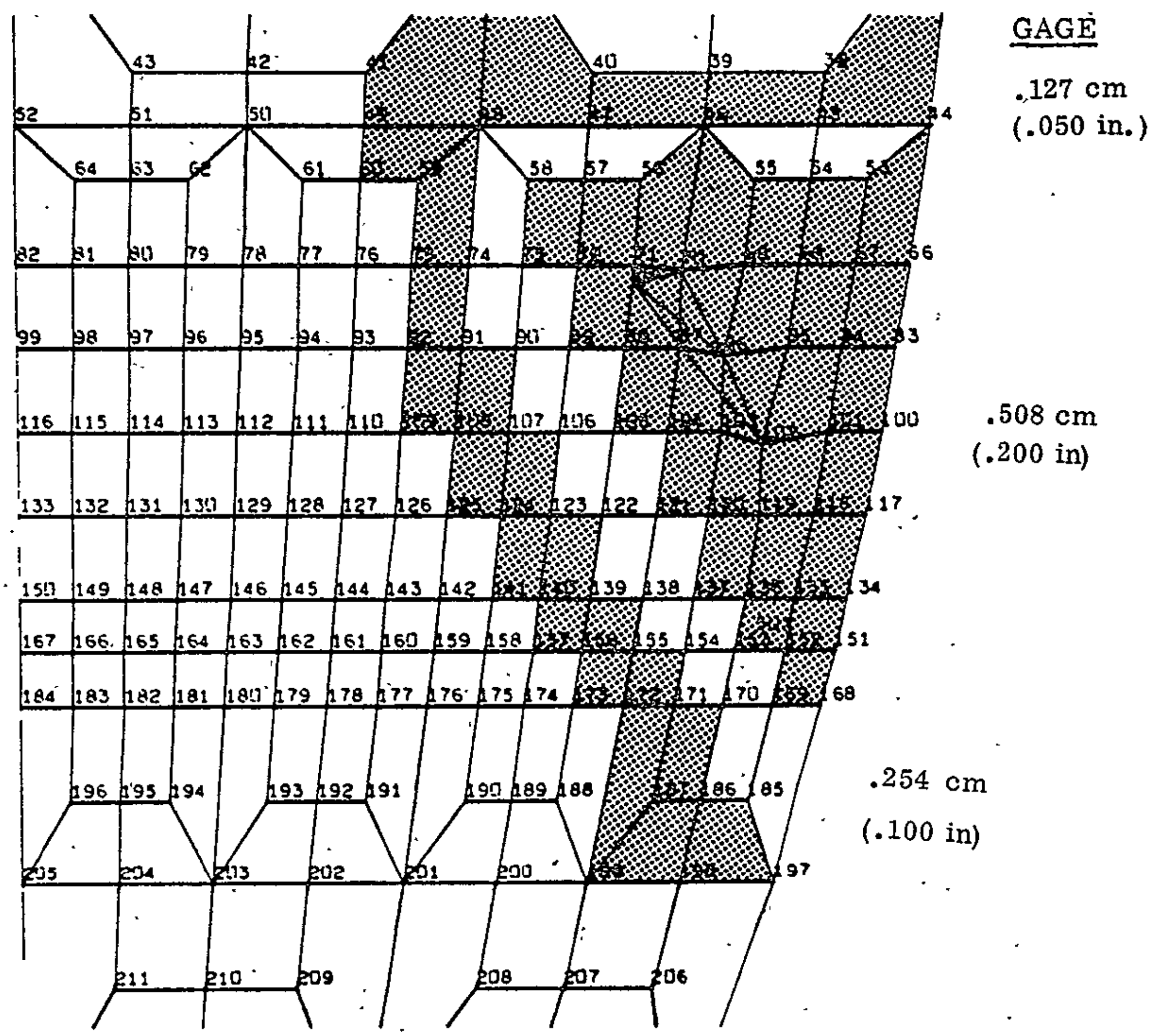


Figure 2-11. Local support pad model half gore.

Primary emphasis was placed on establishing the required local increase in LH_2 tank membrane thickness to account for the membrane load peaking at the six support points. Since the support locations on the bulkhead and the bracket geometry are similar for the LO_2 and LH_2 tanks, results of the detailed computer analysis of the LO_2 tank bracket area were used to evaluate load peaking for the LH_2 tank. The resulting doubler pattern at each LH_2 tank support bracket is similar to the LO_2 tank pattern, except for thicknesses. The LO_2 and LH_2 tank supports are compared in Table 2-1.

Table 2-1. Tank support comparison.

Tank	Maximum Strut Load (kn)	Basic t (cm)	Maximum Land Δ t (cm)	Total Max t (cm)
LO_2	71.17	0.064	0.394	0.457
LH_2	17.79	0.074	0.180	0.187

2.3 GORE/CAP WELDS

2.3.1 LH_2 TANK. A discontinuity stress analysis was performed on the typical tank gore-to-cap weld joint using the Convair discontinuity stress analysis program (P5007).

Maximum stresses in the 0.066-cm thick basic membrane for the critical loading condition (13.7 N/cm^2 internal pressure) are:

$$\begin{array}{lcl} \sigma \text{ membrane} & = & 30.1 \text{ kN/cm}^2 \\ \underline{\sigma \text{ discontinuity}} & = & \underline{1.0 \text{ kN/cm}^2} \\ \sigma \text{ Total} & = & 31.1 \text{ kN/cm}^2 \end{array}$$

which is below the allowable stress of 32.6 kN/cm^2.

2.3.2 LO_2 TANK. Stresses in the LO_2 tank cap-to-gore welds were calculated using results of the LH_2 tank weld joint discontinuity analysis. At the aft cap-to-gore weld joint, the 0.076-cm thick basic membrane is critical for the combined membrane plus discontinuity stresses for internal pressure of 19.3 N/cm^2. Based on the LH_2 tank analysis, the maximum discontinuity stresses are approximately 3% of the membrane stress.

$$\begin{array}{lcl} \sigma \text{ membrane} & = & 29.4 \text{ kN/cm}^2 \\ \underline{\sigma \text{ disc} = 0.03 \text{ membrane}} & = & \underline{0.9 \text{ kN/cm}^2} \\ \sigma \text{ Total} & = & 30.3 \text{ kN/cm}^2 \end{array}$$

which is below the allowable stress of 31.0 kN/cm^2.

2.4 ACCESS DOOR RING JOINT

An axisymmetric finite element analysis was made of the LO_2 tank aft ring joint area. A portion of the shell the thrust cone, and the ring were modeled. The conditions analyzed were: (1) internal pressure only and (2) internal pressure plus thrust loads on the cone. Figure 2-12 shows the deflected shape magnified ten times and overlaid on the undeflected shape. All stresses in the joint area were found to be acceptable. In the areas of the discontinuities, where the tank gage steps from 0.081-cm (0.032-in.) to 0.127-cm (0.050-in.), there is a bending stress introduced which efficiently increases the membrane stress by approximately 30% the meridional stress in the 0.81-cm (0.052-in.) skin is 12,560 N/cm^2 (18,220 psi) by membrane theory or by computer analysis, but this peaks to 16,900 N/cm^2 (24,500 psi) due to differential bending on the element.

An axisymmetric finite element computer analysis model (SOLID SAP) was also generated to evaluate discontinuity stresses due to the LH_2 tank access door seal ring. A segment of the door membrane, the door ring, and a segment of the tank membrane were included in the model. Discontinuity stresses were calculated for the critical loading condition of 13.7 N/cm^2 maximum design ullage pressure. A picture of the model is shown in Figure 2-13.

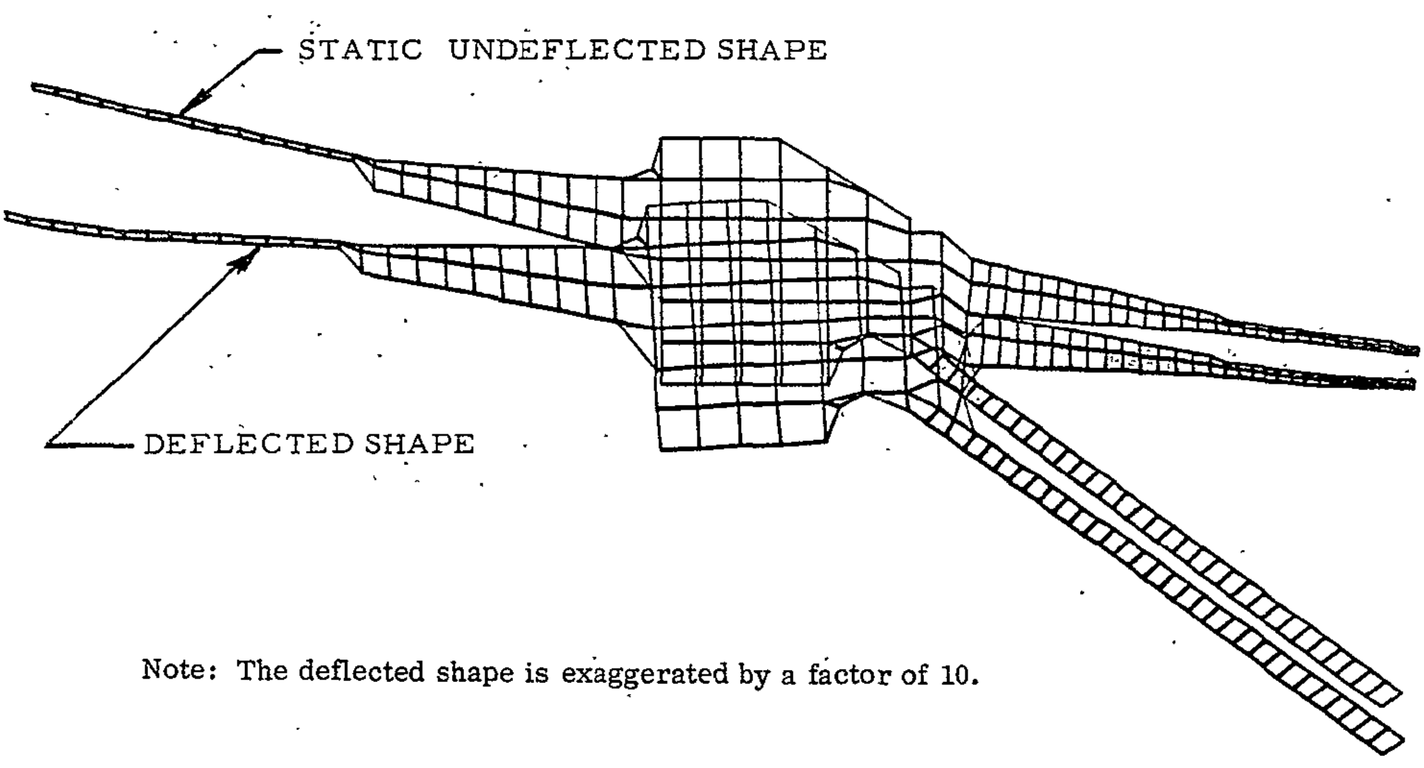


Figure 2-12. LO_2 door/cone deflection.

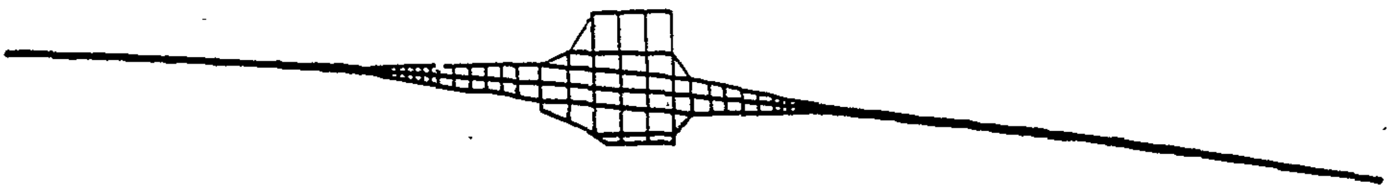


Figure 2-13. Solid SAP model.

Maximum stresses from the analysis are tabulated in Table 2-2.

Table 2-2. Door ring analysis — maximum stresses.

Location	t (cm)	$\sigma\phi$ membrane (kN/cm^2)	$\sigma\phi$ disc (kN/cm^2)	$\sigma\phi$ total (kN/cm^2)	$\sigma\phi$ allow (kN/cm^2)	M.S.
Tank Membrane	0.084	27.8	3.3	31.1	32.5	+0.04
Tank Weld	0.183	12.8	4.5	17.3	17.3	+0.00
Door Membrane	0.084	28.4	2.7	31.1	32.5	+0.04

2.5 LATERAL LOADING EFFECTS

One of the design loading conditions for the LO_2 tank is shuttle liftoff. During this condition the tank experiences a lateral load of 1.36 g. This side loading tends to put local hoop compression in the tank wall near the girth. An analysis was performed using this condition and it was determined that hoop compression will exist in a region from ϕ = 1.14 radians to ϕ = 2.27 radians for approximately halfway around the tank. (See Figure 2-14.) Figure 2-15 shows a plot of hoop loads at ϕ = 1.14 radians, where compression is just beginning. Figure 2-16 shows the maximum compression around the girth and Figure 2-17 shows ϕ = 2.27 radians, where compression is minimal again. In the regions were ϕ is less than 1.14 radians and where ϕ is greater than 2.27 radians, there will be no hoop compression under this condition. The skin gages necessary to resist these hoop loads are shown in Figure 2-18.

The design solution analyzed at this point was simply an increase in tank wall thickness (monocoque). Integral, internal ring stiffeners have also been investigated.

The design approach was to find a balanced design, considering local skin buckling between the stiffeners, and overall general instability of the tank. A parametric study was made, varying stiffener spacing, stiffener I section, and skin gage. Figure 2-19 shows a plot of the required shell gage vs stiffener spacing for various stiffener cross sections. This case is based on general instability only, and does not account for local shell buckling between stiffeners. Therefore, Figure 2-20 must be used in conjunction to give the required shell strength, depending on stiffener spacing.

An optimum configuration for hoop compression stiffening is presented in Figure 2-21. Equivalent shell thickness is plotted vs required compression allowable. The stiffener configuration selected is shown in Figure 1-3. Stiffener size decreases as you move away from the girth, since the load intensity decreases allowing a decrease in required N_{cr}.

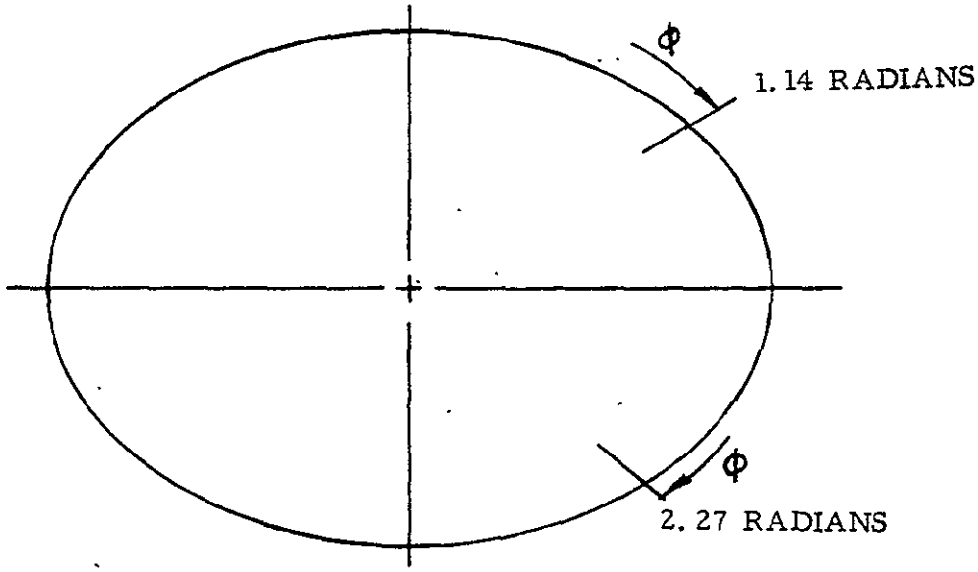


Figure 2-14. Ellipse compression zone for side loads.

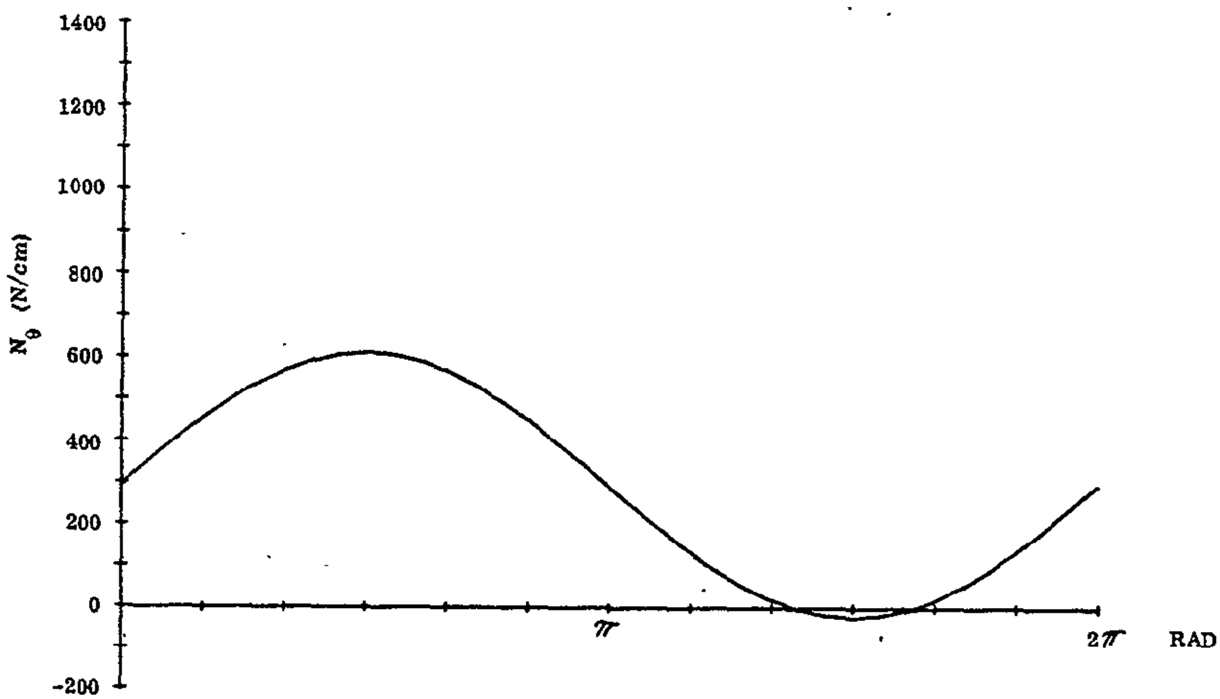


Figure 2-15. Hoop line at PHI = 1.14 radians (65°).

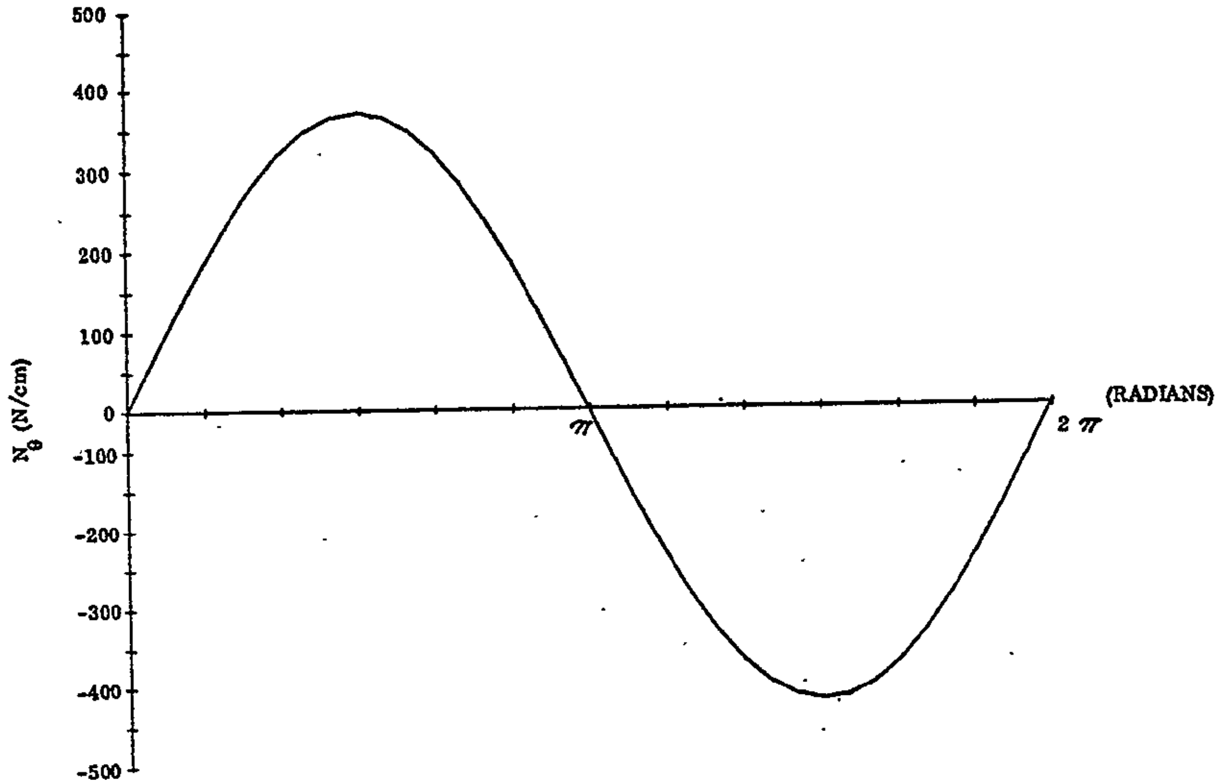


Figure 2-16. Hoop line loads at girth.

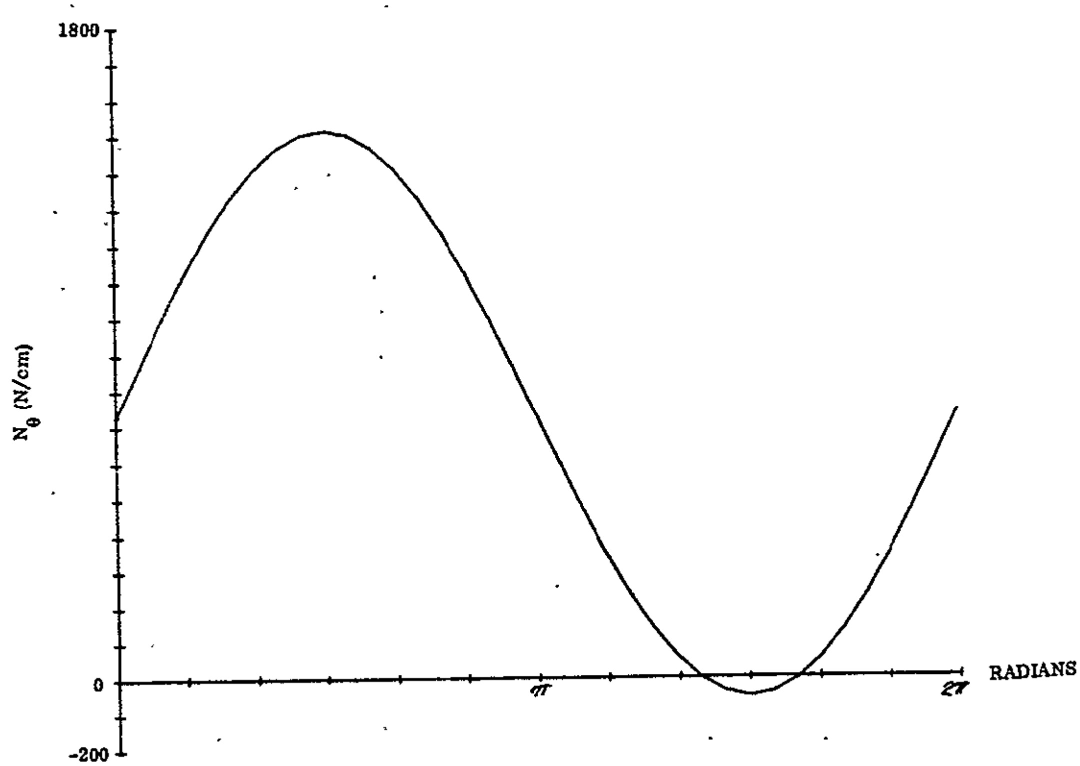


Figure 2-17. Hoop line load at PHI = 2.27 radians (130°).

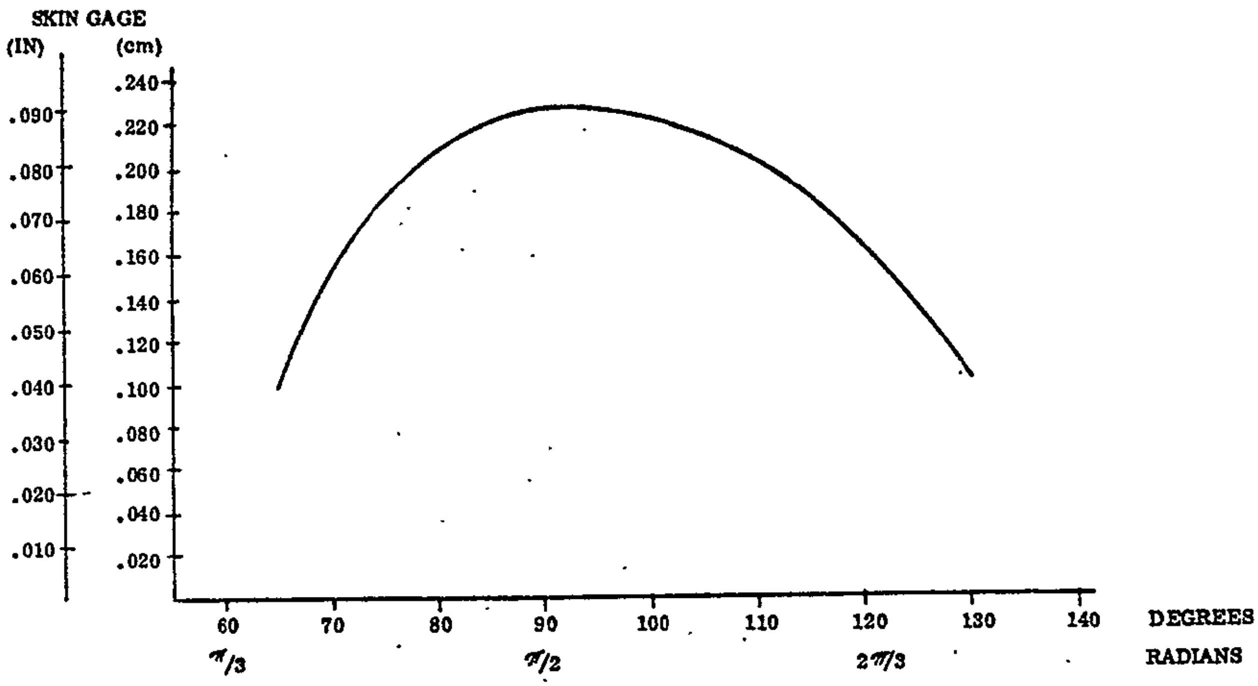


Figure 2-18. Gage requirement due to side loading.

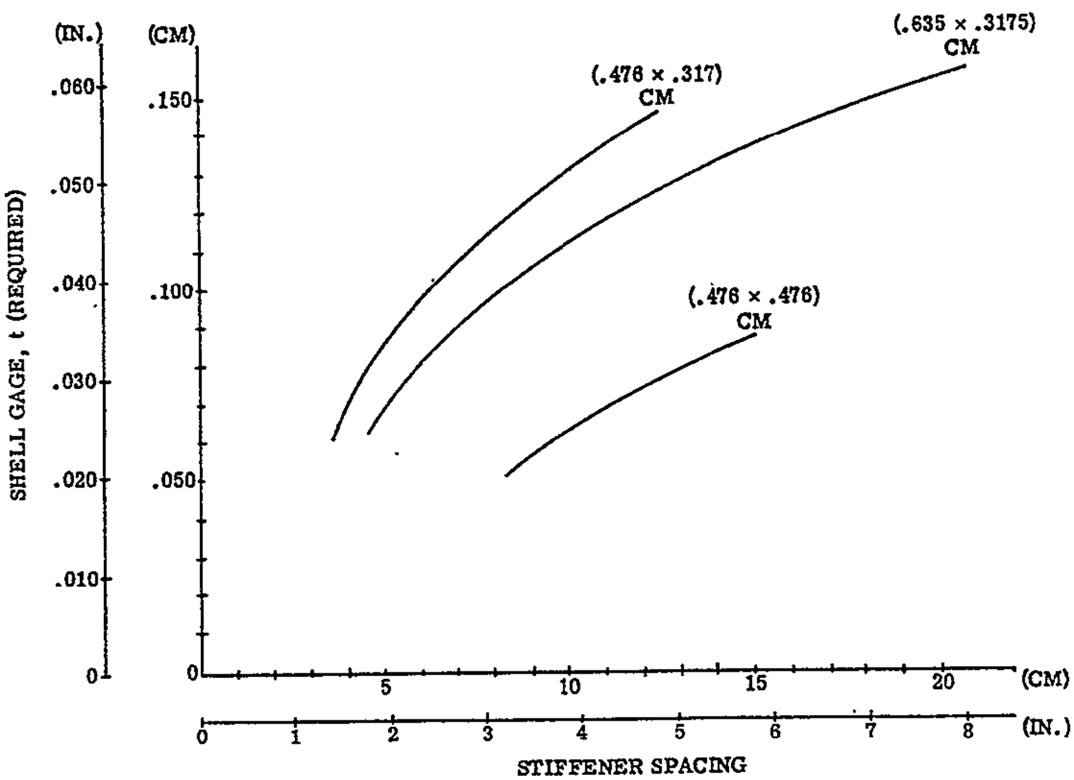


Figure 2-19. General instability.

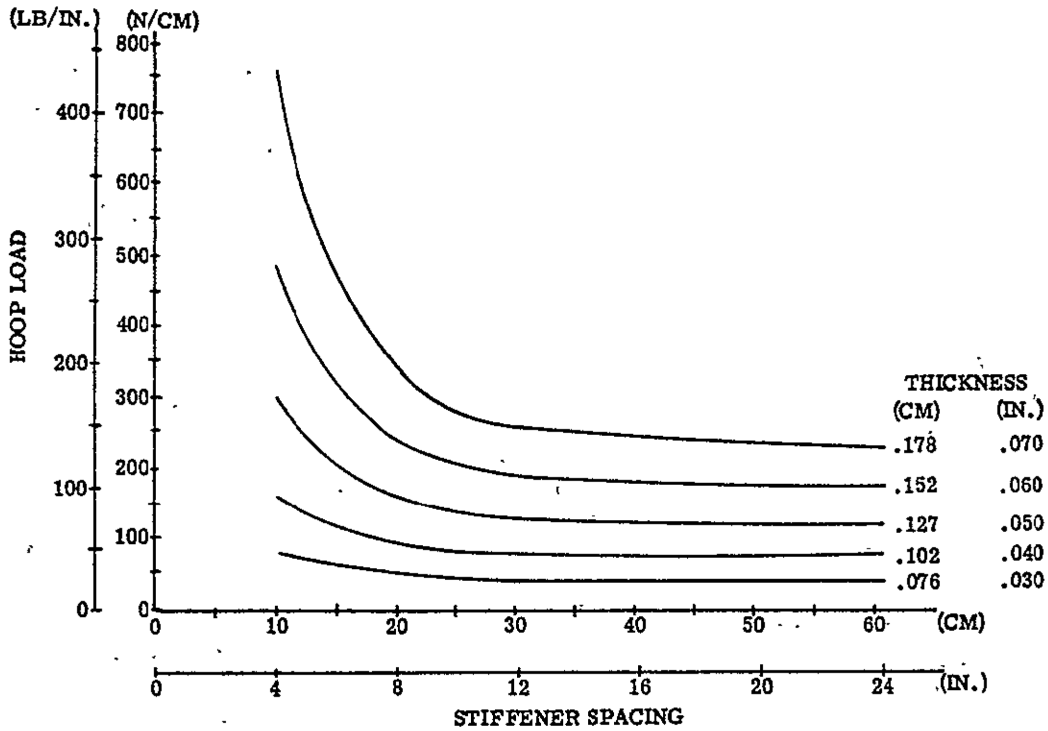


Figure 2-20. Critical hoop compression loading.

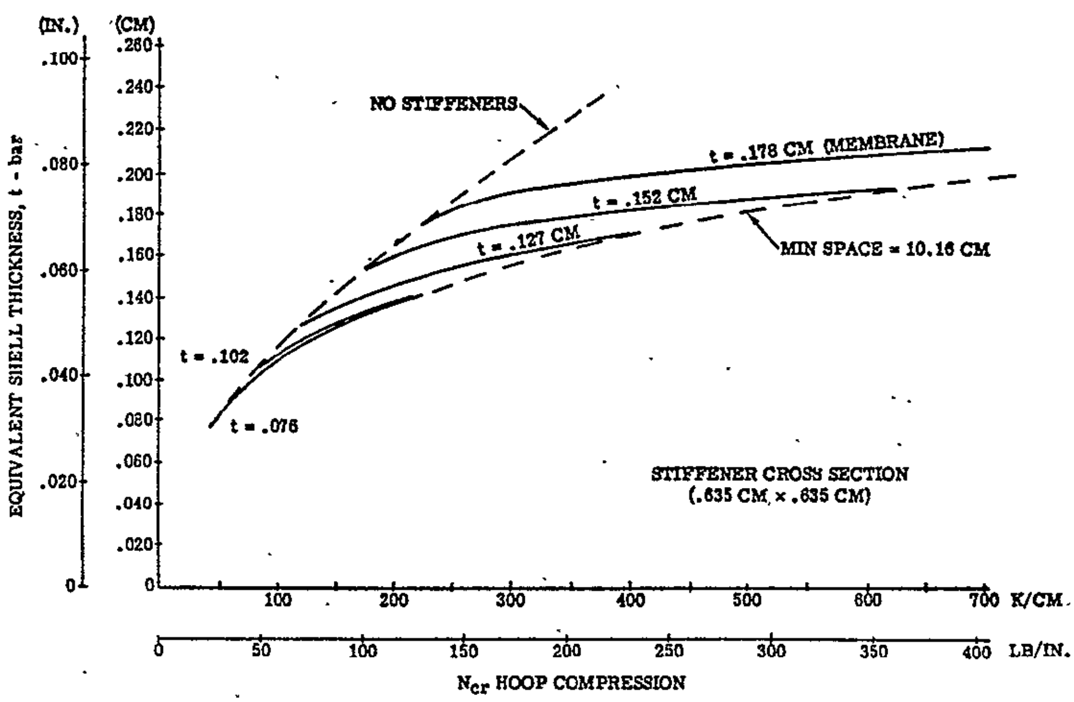


Figure 2-21. Optimum configuration hoop compression stiffening.

3

TEST TANK DESIGN

The objective of this task was to produce detailed test tank design drawings.

The selected test tank configuration was based on the predesign LO_2 configuration: an ellipsoidal contoured shell with a laced type support strut system. The predesign tank was scaled to a 3.048-meter major diameter for the test tank, resulting in a 5/6-scale model. This scale maximized the use of the existing Centaur tank forming and welding tooling. The test tank assembly drawing is shown in Figure 3-1. The special features identified in this study as requirements for a Tug LO_2 tankage system have been incorporated in this design. The access door located in the aft bulkhead is flush-mounted, with main engine thrust cone support provisions near the outer diameter encircling the tank fill and drain outlet in the center of the door. The door is 57.1 cm in diameter, machined from a 2024T851 plate. The membrane is contoured to a 205.7-cm radius.

Circumferential membrane stiffening to redistribute side load stresses has been defined, based on the predesign LO_2 tank concept. The stiffeners are ribs chem-milled into each individual gore and equally distributed on either side of the girth weld. The strut support system requires a weldment pad (a thicker area to account for allowable reduction of the membrane due to welding effects) and a stress redistribution zone as outlined for the Tug tank. The test tank pad triangle and the transition steps are sized to represent that support system. The tank membrane gages were selected to produce stress levels equal to those expected in the Tug LO_2 flight tank.

Detail designs were produced for the door, door ring, outlet, gore forming, gore chem milling, tank welding, support structures, and assembly. These designs were reviewed by stress, quality assurance, and manufacturing personnel prior to release to the factory for fabrication.

The door ring outside diameter is 67.6-cm with a center opening of 51.8 cm. The ring is machined from a 2219T852 roll ring forging and represents a continuation of the shell contour when butt welded into the bulkhead. Thirty six inserts are provided for door attachment.

The tank forward outlet boss has a 9.8-cm diameter bell-shaped opening. It is machined from a 30.5-cm 2219T87 aluminum alloy plate. Like the door ring, the base is butt welded into the bulkhead and forms a continuation of the bulkhead contour.

The gore and cap pieces are cut and formed from 0.3175-cm-thick 2219T37 aluminum alloy sheet. The gores are formed to contour in 0.52-radian sections then aged to 2219T87 before chemical milling to the required surface pattern and thicknesses. The gores are butt welded together to form bulkhead subassemblies. At the subassembly level, the outlet base is installed, with cap, door ring, and brackets. The tank shell is completed when the forward and aft bulkheads are welded at the girth.

A fracture control plan was developed based on the plan presently used on the shuttle mid-fuselage fabrication program. The test tank fracture control plan is presented in Appendix B.

4

TEST TANK ANALYSIS

The objective of this task was to perform complete structural analysis on test tank (subscale) design.

4.1 REINFORCEMENT AT SUPPORT BRACKETS

A finite element model was constructed, similar to the one used for the predesign tank, but with a finer mesh. The overall model is shown in Figure 4-1. Figure 4-2 shows the modeled land area where the fitting attaches to the shell. The center portion of the land is 0.254-cm (0.100-in.) thick, stepping down to 0.191-cm (0.075-in.), 0.127-cm (0.050-in.), and finally the basic 0.064-cm, (0.025-in.) in 2.54-cm (1.00-in.) bands.

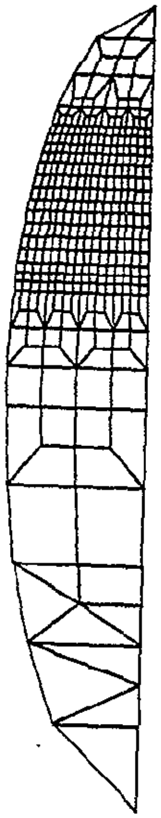


Figure 4-1. Gore model.

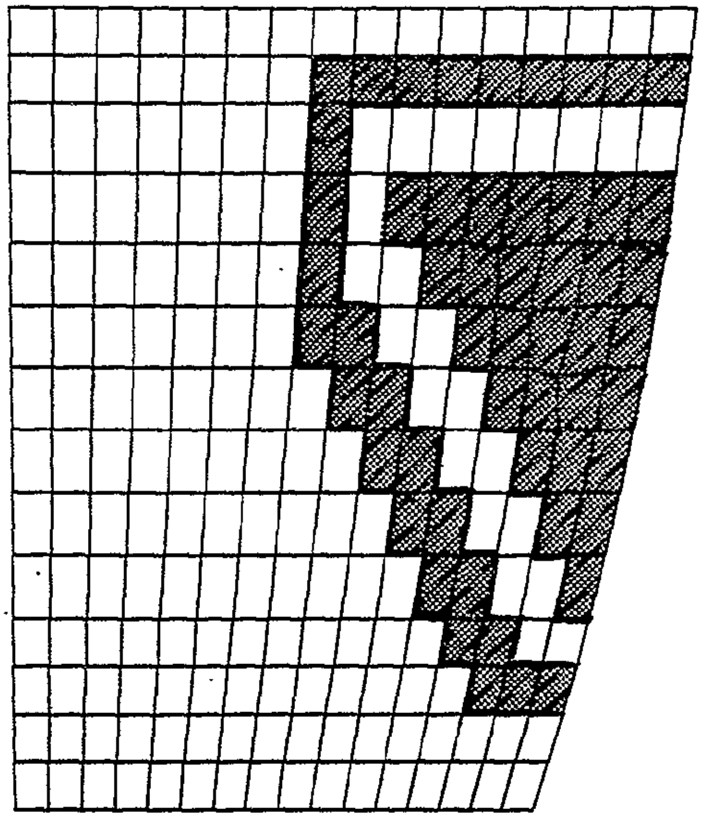


Figure 4-2. Support pad model.

Two conditions were analyzed: the first for a uniform internal pressure; and the second for the effects of hydrostatic head pressure. Stress contour plots have been generated from the analytical results, using a graphic interface to the digital computer. Figure 4-3 depicts the hoop stress contours for uniform internal pressure of 18.6 N/cm^2 (27.0 psi). The contour lines would normally be circumferential, if the shell thickness is constant. Figure 4-4 illustrates the meridional stresses for the same loading condition. Note the decrease in stress as the shell thickness increases.

The hoop stress distribution for the hydrostatic head condition (supported by the tangential struts) is shown in Figure 4-5. Note the high tensile hoop stresses above the strut attach point. These must be added to the uniform pressure stresses to give the total stress distribution in the shell. Figure 4-6 gives the meridional stress distribution for the hydrostatic head condition. As expected, there are high tensile stresses below the fitting and meridional compression above the support point. The combined meridional stresses (including the pressure effects) are tensile above the support point.

4.2 SIDE LOADING

The test tank is subjected to the same hoop compression phenomena from lateral loads as the predesign tank. But, due to the lesser load (1.0 g as opposed to 1.36 g on the predesign tank), the lower density fluid, and the smaller size, the severity of the problem is lessened. However, the buckling allowables of this skin between stiffeners does not increase appreciably, since the R/t is still very large. Test tank hoop compression curves are shown in Figures 4-7, 4-8, and 4-9 for ϕ = 0.52, 1.09, and 1.57 radians, respectively, for zero internal pressure. Increasing the internal pressure reduces the hoop compression in this tank. Table 4-1 gives the relationship between max N_θ at ϕ = 1.57 radians vs ΔP.

A shell gage of 0.094-cm (0.037 in.) has been selected in this area of the hoop compression, allowing a reasonable span between ring stiffeners while maintaining shell gage continuity with the 0.094-cm transition step. Figure 4-10 presents a family of curves for various stiffener depths showing allowable hoop compression (N_{cr}) versus spacing between stiffeners. At 15.24-cm (6.0-in.) spacing, the 0.254-cm-deep stiffener can resist a 142-N/cm compressive force, whereas the skin has an allowable compressive capability of 106 N/cm. The test tank will be pressurized during side load testing to 10.3 N/cm^2 (15.0 psi), which will yield a maximum hoop compression load intensity of 96 N/cm. This will give a positive margin of safety of 10 percent in the skin.

The test tank stiffeners have been sized to give maximum spacing, producing general instability equal to local skin buckling. The ullage pressure will then be selected to preclude shell buckling with the tank in the horizontal position.

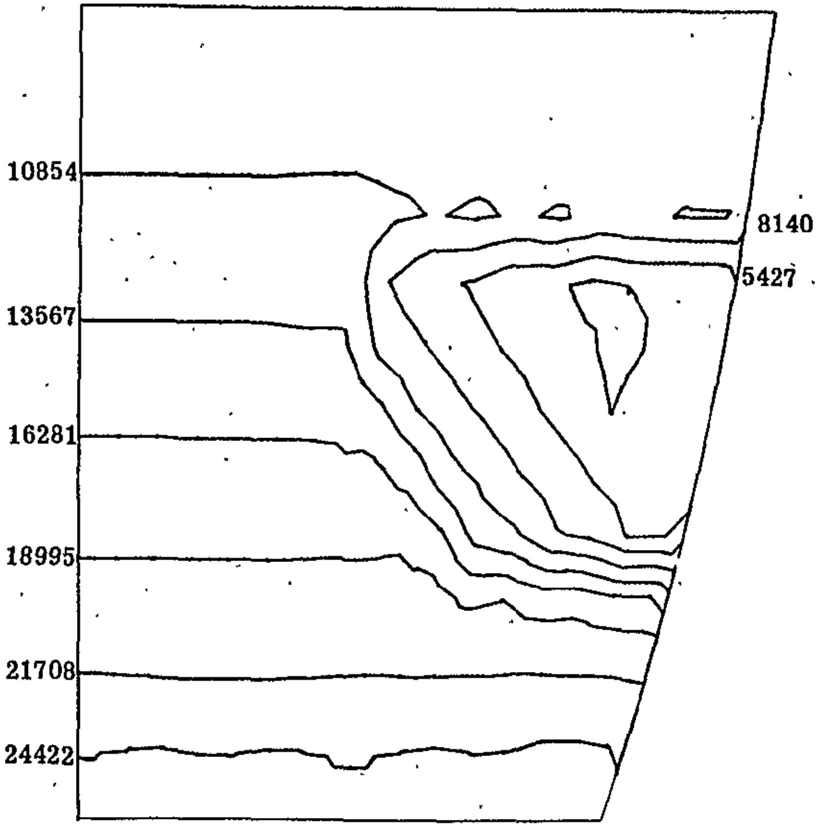


Figure 4-3. Hoop stress contours for uniform pressure.

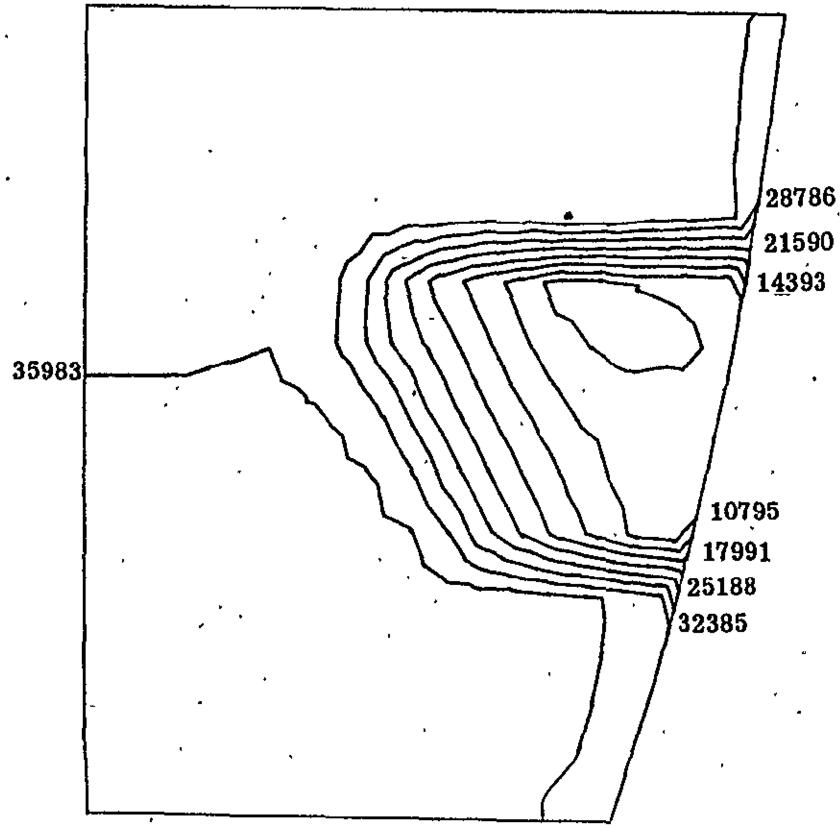


Figure 4-4. Meridional stresses for uniform pressure.

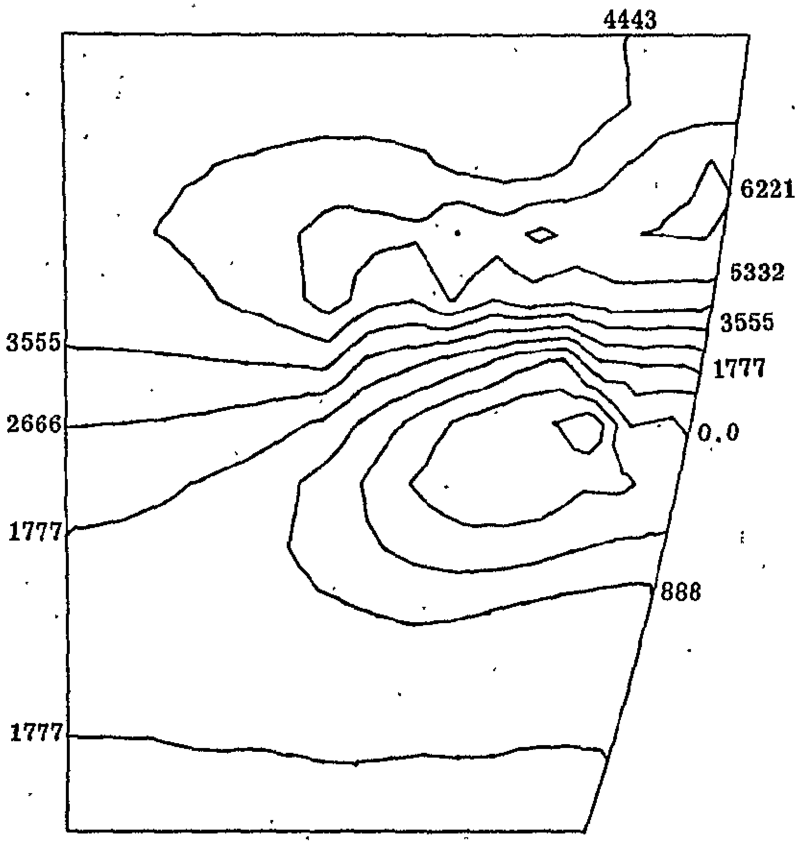


Figure 4-5. Hoop stress contours for hydrostatic pressure.

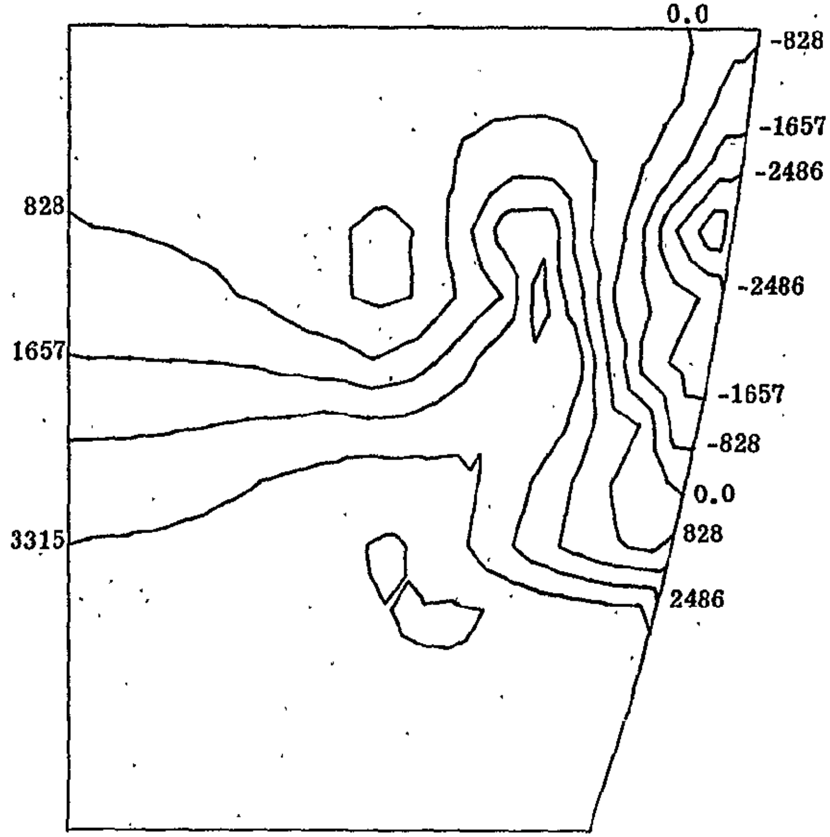


Figure 4-6. Meridional stress contours for hydrostatic pressure.

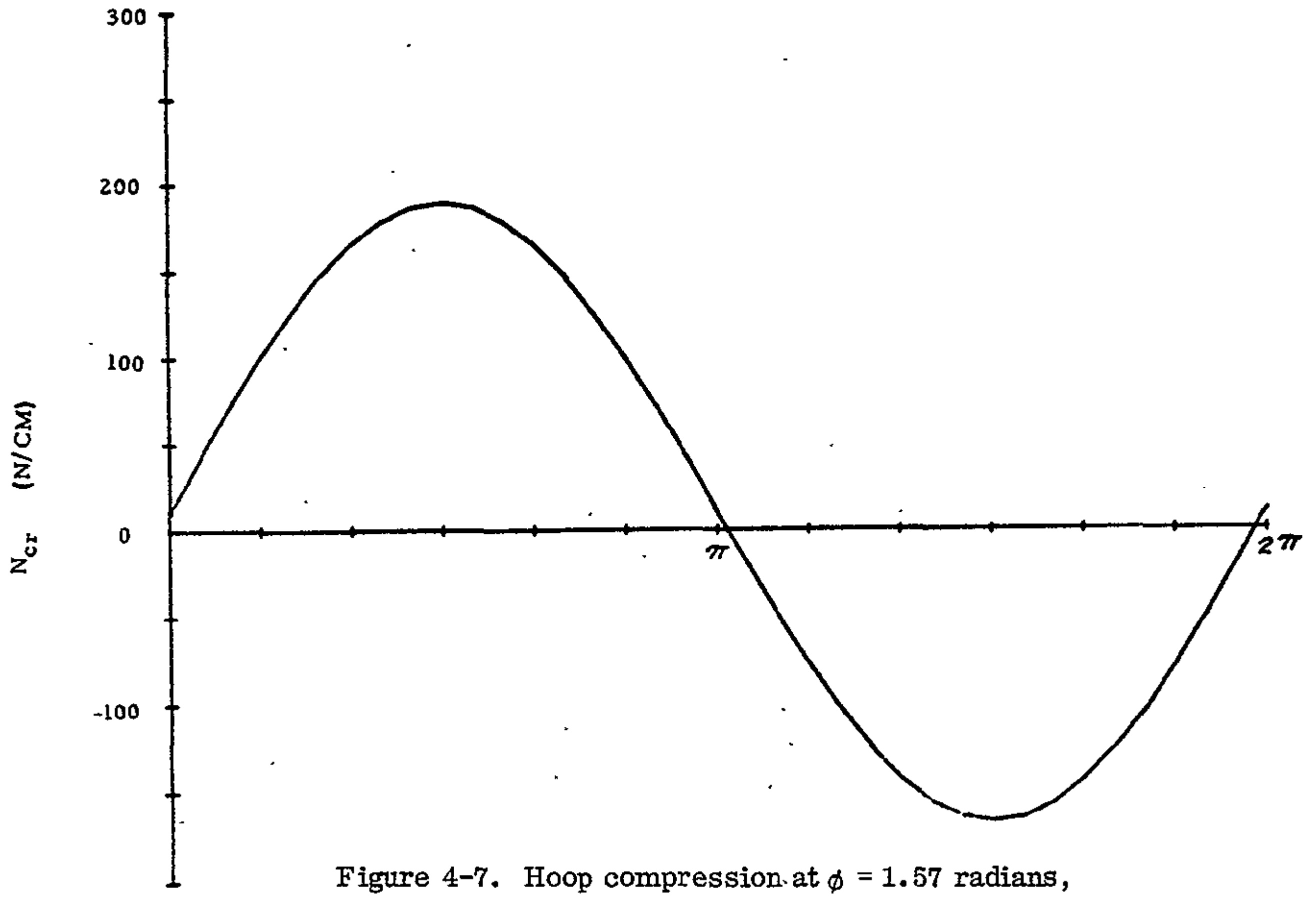


Figure 4-7. Hoop compression at ϕ = 1.57 radians, ullage pressure ≐ 0.

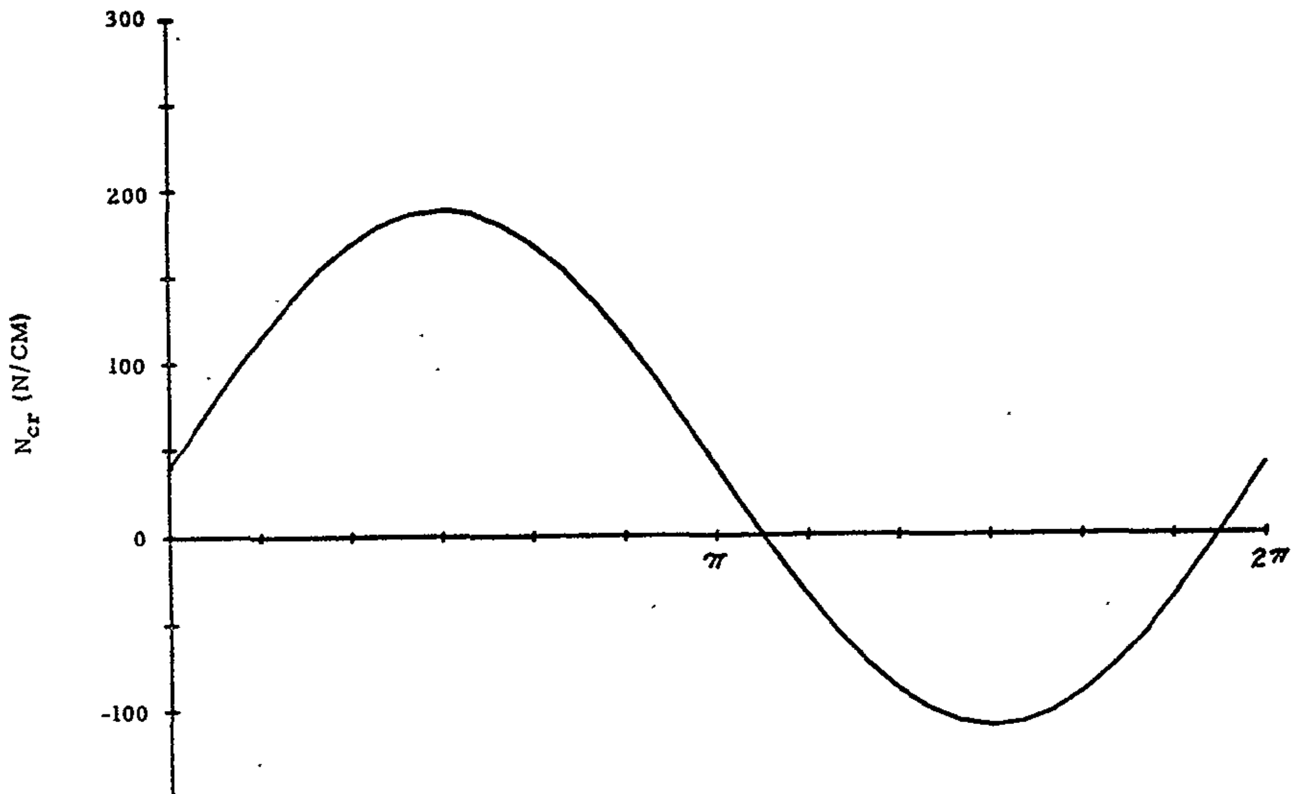


Figure 4-8. Hoop compression at ϕ = 1.05 radians, ullage pressure = 0.

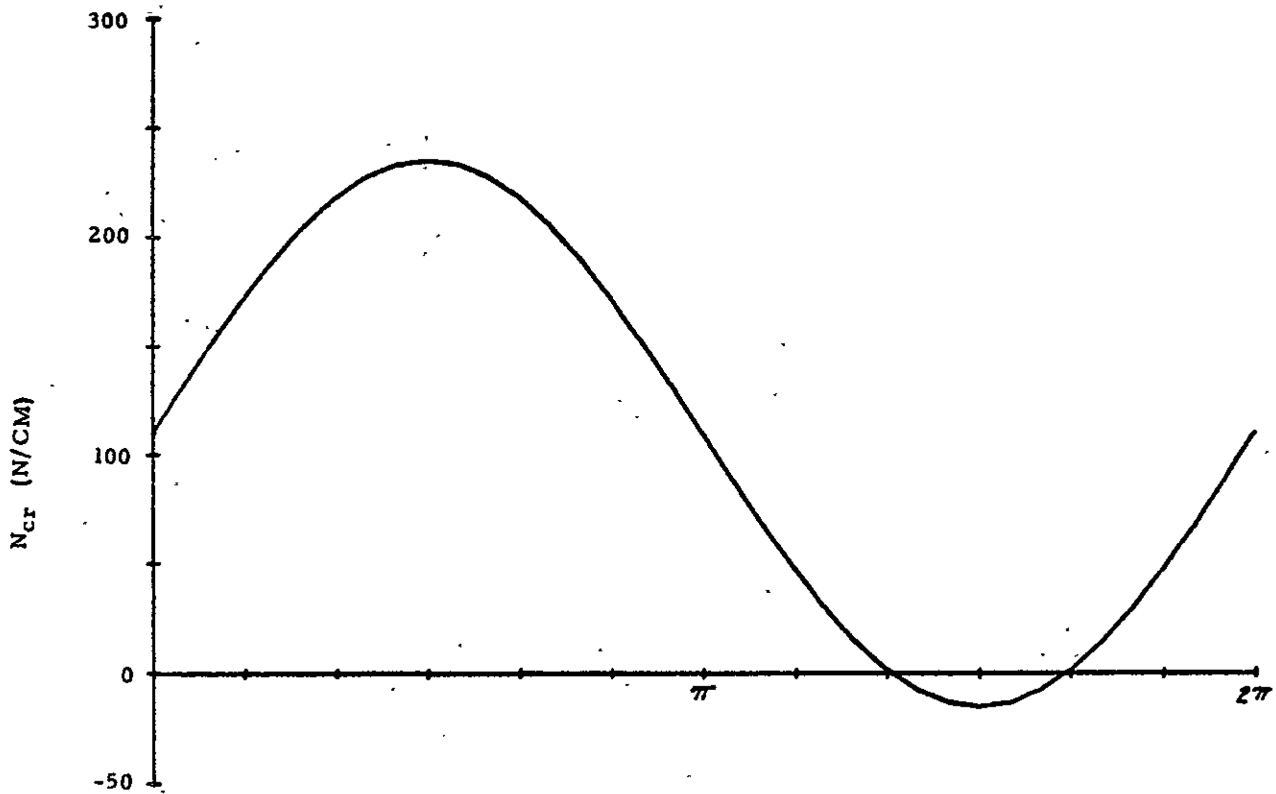


Figure 4-9. Hoop compression at ϕ = 0.52 radians, ullage pressure = 0.

Table 4-1. Hoop compression loads variation with ullage pressure.

Ullage Pressure		Hoop Load	
N/m^2	PSI	N/cm	LB/IN.
0	0	165	94
6.89	10	116	66
10.34	15	91	52
12.41	18	77	44
13.10	19	72	41
13.79	20	67	38

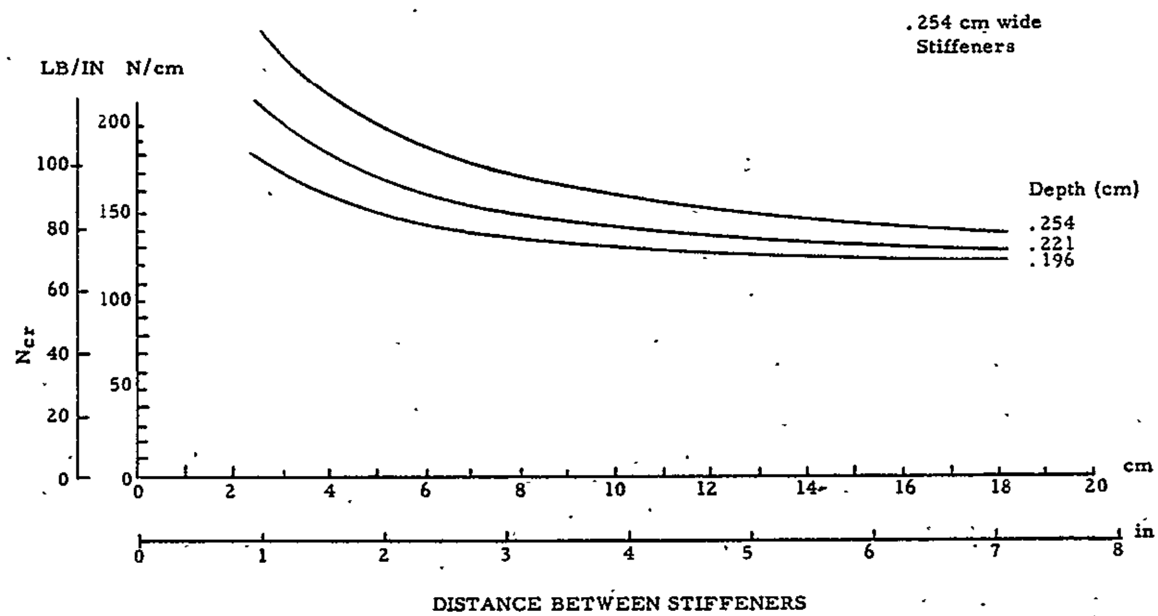


Figure 4-10. General instability of test tank.

4.3 AFT RING CONFIGURATION

The aft ring joint, which includes the thrust cone interface, has been analyzed using the Solid SAP finite-element computer program. The analysis model is shown in Figure 4-11. It is an axisymmetrical analysis addressing two loading conditions. This analysis is similar to that done on the predesign tank, except that the mesh size has been refined.

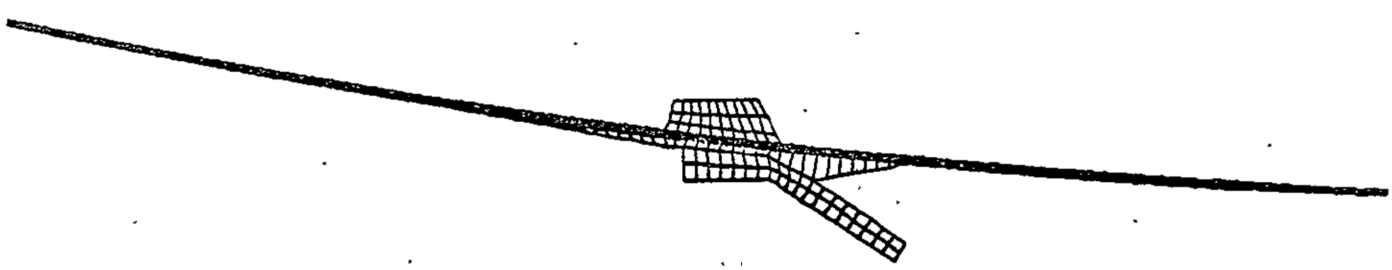


Figure 4-11. Door/ring/membrane computer model.

On the test tank, the basic shell gage builds up from the 0.064-cm (0.025-in.) skin to 0.127 cm (0.050 in.) as it attaches to the ring. The joint has been analyzed using uniform internal pressure alone, as well as with thrust loads in conjunction with internal pressure. Figure 4-12 is an enlargement of the computer model in the area of the ring joint to show more detail. The model is shown in the undeflected shape. Figure 4-13 shows the same enlarged area but deflected due to internal tank pressure; the deflections are magnified by a factor of five.

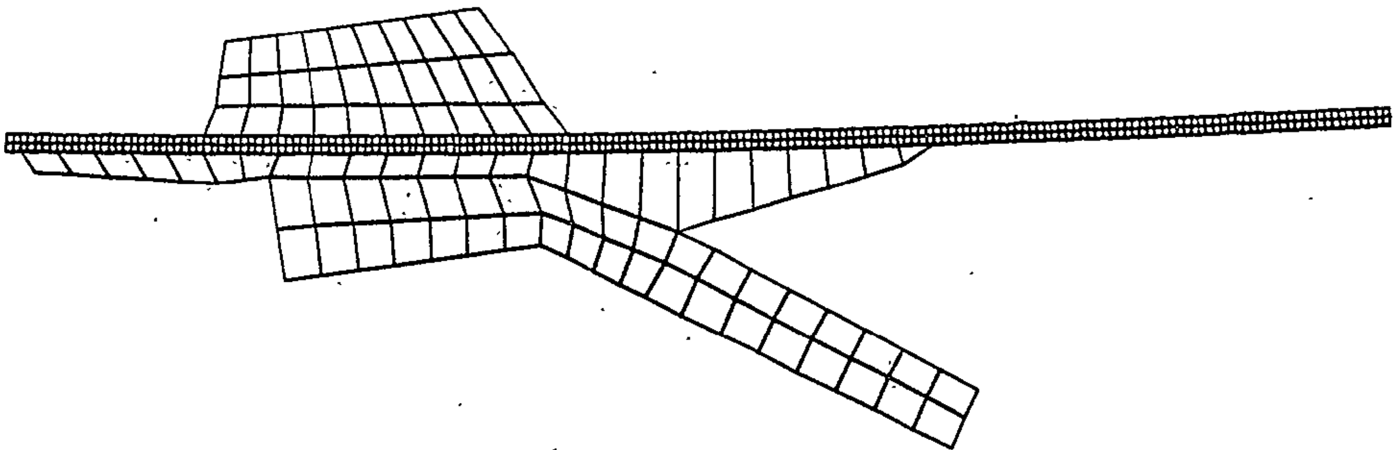


Figure 4-12. Door/ring joint model detail.

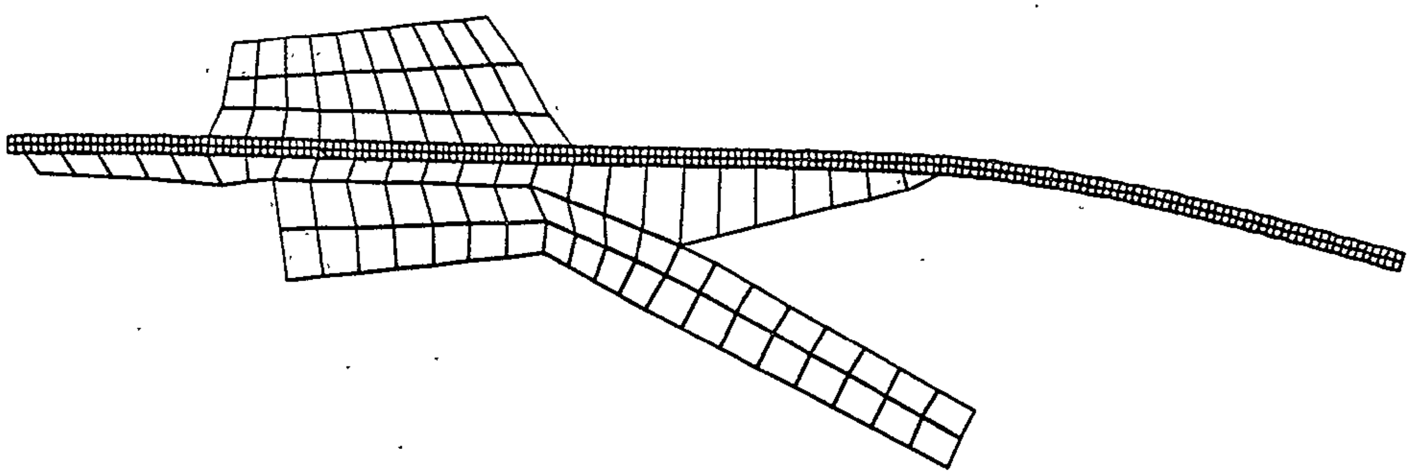


Figure 4-13. Door/ring joint deflected model (magnified 5 times).

The analysis has shown that the discontinuity stresses at the steps in the shell are within the allowable values and that the tank ring is adequate to react the thrust loads imposed upon it.

5

FABRICATION PROGRAM OUTLINE

The objective of this task was to develop a fabrication program outline for the test tank. The outline that was developed is presented in this Section.

LIGHTWEIGHT OXIDIZER TEST TANK
CONTRACT NAS 8-31370
MANUFACTURING PLAN OUTLINE

MATERIAL LIST:

Item	Qty	Stock Size *	Material
Gores	24	0.125 x 48 x 144	2219-T37
Cap	1	0.125 x 26.50 dia.	2219-T37
Ring	1	1.20 x 20.0 x 27.0	2219-T852
Door	1	2.0 x 22.5 dia.	2024-T851
Outlet	1	1.5 x 9.1	2219-T852
Bracket Supports	24	0.5 x 1.25 x 4.20	2219-T852
Weld Filler Wire	3	100 Ft. Rolls	2319
Bolts	36	NAS 1005-4	
Washers	36	AN 960 PD 516	
Inserts	36	MS 21209F5-15	
Metal "O" Ring	1	0.125 dia. x 0.010 Wall x 21.0 nominal O.D.	321 SS
Metal "O" Ring	2	0.125 dia. x 0.010 Wall x 2.75 nominal O.D.	321 SS
Bearings	24	MS 21155-B4	

*Shown in conventional stock units.

Material to conform to the following specifications:

2219-T37	QQ-A-250/30
2219-T852	QQ-A-367
2319	GDC 0-00810-2
	MIL Spec QQ-R-5662319

DETAIL MACHINING - Raw stock will be machined per design requirements into:

	Part Number
One Ring	PD 75-0124
One Door	PD 75-0122
One Outlet	PD 75-0126
Twenty-four Tank Support Brackets	PD 75-0125

GORES - Part No. PD 75-0121 — 24 Required

The gore blanks will be stretch formed on the existing Centaur ellipsoidal bulkhead gore stretch form (STFM) die. The formed gores will be marked for trimming with a trim template and rough trimmed. The formed gores will be alkaline cleaned and deoxidized using existing production facilities. Each gore will then be precipitation aged to the T87 condition in an aging fixture. The membrane area of the gores will then be chem-milled on one or both sides after being masked off. The gore will again be alkaline cleaned and deoxidized. Weld joint areas around the edges of the gores will be masked off and the gores will be conversion coated to prevent corrosion. The gores will then be net trimmed per design specifications. This will be accomplished by layout or by a new trim fixture.

BULKHEAD SUBASSEMBLY (Figure 5-1)

Weld schedules will be developed per MIL-W-8604 for the following: gore-to-gore weld, gore-to-ring weld, gore-to-cap, and tank major weld.

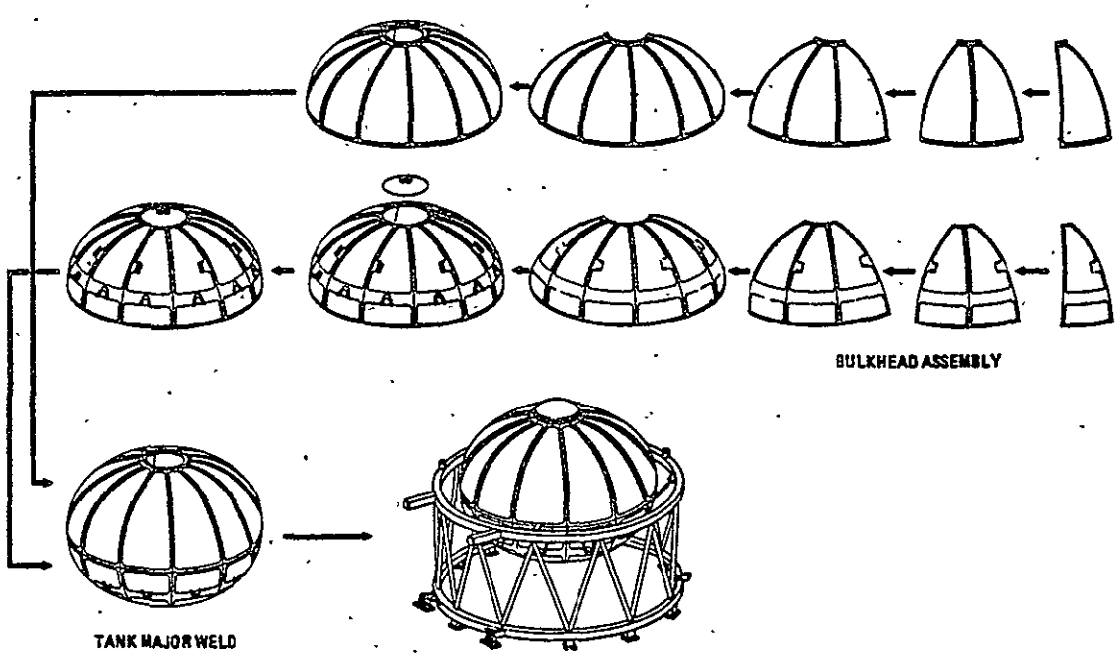


Figure 5-1. Manufacturing flow sequence.

The gore-to-gore welds will be accomplished in existing holding fixture WLFX 7-73101-574 (temporary modification of the tool will be required, and a provision for wire feed will be required). An automatic tungsten inert gas welding (TIG) process will provide weld quality per MIL-W-8604 and design requirements. Gore sections will be fit to the holding fixtures, scraped and welded to form complete ellipsoidal bulkheads. The bulkheads will be individually moved using an existing handling tool (HATO 7-73101-574) and installed in existing holding fixture WLFX 55-72323-570 for welding gore-to-ring (temporary modification of WLFX required) and gore-to-cap welds. The joints will be scraped and welded using the existing pulsation welding power supply with the automatic TIG welding process. The bulkheads will be individually checked in an existing bowl-type check gage (CKGA 7-3101-574), the widest bulkhead radii will be scarfed and matched for the tank major weld. After the bulkheads are removed from the check gage the external supporting brackets will be fusion welded in place per MIL-W-8604 and design requirements. (NOTE: Where existing tool modification is impractical, a tool will be made or an alternate method used for manufacture.)

TANK MAJOR WELD - A special weld fixture must be designed and fabricated for weld alignment and support of both sides of the major girth weld. The fixture with internally supported backup bars rotates the tank about a horizontal axis under the weld torch. The Tektron pulsation power supply with TIG welding process will provide weld quality per MIL-W-8604 and design requirements. A single continuous weld will join the two bulkheads to form the tank. The backup tooling will be disassembled and removed through the ring opening.

TANK WASH AND PRE-FINAL INSTALL - The tank will be installed in the tank support fixture and solvent washed inside per spec GDC-MOS 1-02513. The untreated weld areas will then be conversion coated. After final inspection per the engineering drawing requirements, the tank will be transferred to the test department for proof pressure testing and the subsequent engineering test program.

6

TEST PROGRAM OUTLINE

The objective of this task was to prepare a test program outline for the test tank design evaluation test. The resulting test tank test procedure is presented in Appendix C.

6.1 SUMMARY

The lightweight propellant tank test article is to be supported in a combination handling and test fixture provisioned with hinges so as to permit tipping on its side, thereby enabling tests to be performed in both the vertical and horizontal positions. The test article will be instrumented with 38 rosette strain gages on the external surfaces and an equal number positioned identically on the internal surfaces. Uniaxial strain gages will be used on each of the supporting struts and linear motion transducers employed for measuring test article deflections.

The test article, positioned vertically, is initially to be hydrostatically proof pressure tested. Following the proof pressure test, test runs are to be made in which cata is to be recorded for different ullage pressures at each of three fluid levels, empty, 1/2 full, and full,. with the test article in the vertical positions using water as the test fluid. The test with the test article full is to be repeated with the test article in the horizontal position.

6.2 TEST OBJECTIVES

The objectives of the lightweight propellant tank design evaluation test are:

a. Demonstrate the structural integrity of the test tank.

b. Validate the analyses techniques used for tank design.

c. Provide design data in the areas of stress redistribution discontinuity and compression buckling.

6.3 TEST CONFIGURATION

The test article, a 3.05m (10 ft) diameter ellipsoidal lightweight propellant tank, will be suspended by 24 struts in a combination handling and test fixture provisioned with hinges to permit tipping on its side, thus enabling testing in both the vertical and horizontal positions. (See Figure 6-1.) The test setup will include provisions to allow application of a 66.7 kN (15,000 lb) engine thrust load to the test article. Filling and

draining of the test tank with water and measurement of the water level will be accomplished through the tank penetration at the bottom of the tank. Instrumentation leads will exit the tank through the outlet in the top of the tank. The test setup will include a system for pressurizing to and maintaining the test article at test pressures. This system will be equipped with appropriate safety provisions to prevent inadvertent over-pressurization or evacuation of the test tank.

Test article instrumentation will consist of strain gages and deflection transducers. Strain gage instrumentation shall be located as shown in Table 6-1.

Table 6-1. Strain gage instrument locations.

Location	Type	No. of Gages Internal	No. of Gages External
Door ring	Rosette	6*	6*
Gore splices	Rosette	4*	4*
Girth splice	Rosette	4*	4*
Support bracket	Rosette	18*	18*
Hoop compression near girth	Rosette	6*	6*
Support struts	Uniaxial	24	
Cone		8	

*The internal/external gages will be positioned "back-to-back".

Approximately 12 linear motion transducers will be positioned around the test article (exact location to be determined at a later date) to provide test article deflection measurements. Data shall be recorded at each test increment by automatic instrumentation recorders.

6.4 TEST CONDITIONS

All testing will be performed at the ambient environmental conditions existing at the time of the test. No attempt will be made to control the test article temperature.

The water used in the test article is to be distilled — deionized water.

6.5 TEST PROCEDURE/SEQUENCE

6.5.1 PROOF PRESSURE TEST. With the test article empty and in the upright position pressurize the tank to 19.5 N/cm^2 (28.3 psig) (1.05 × Design Limit Pressure).

6.5.2 <u>DESIGN PRESSURE, AXIAL HEAD TEST</u>. With the test article in the upright position record all instrumentation for each of the load conditions shown in Table 6-2 at pressurization increments of 2.5 N/cm^2 (3.62 psi).

Table 6-2. Test article load conditions.

Ullage Pressure N/cm^2 (psig)	Liquid Level	Thrust Load N/cm (lb/in.)
0 to 18.6 (27.0)	Empty	0
0 to 17.5 (25.4)	1/2 Full	0
0 to 16.5 (23.9)	Full	0

6.5.3 <u>ENGINE THRUST LOAD TEST</u>. With the test article in the upright position, full and pressurized to 16.5 N/cm^2 (23.9 psig), load the thrust cone from 0 to 243.15 N/cm^2 (138.84 lb/in.) of thrust cone circumference in increments of 25 N/cm (14.3 lb/in.). Record all instrumentation at each increment.

6.5.4 <u>DESIGN PRESSURE, LATERAL HEAD TEST</u>. With the test article full and positioned on its side pressurize the tank from 0 to 18.6 N/cm^2 (27 psig) in increments of 2.5 N/cm^2 (3.62 psi). Record all instrumentation at each increment of pressure.

This test program outline was expanded into the complete test procedure presented in Appendix C.

7

MANUFACTURING OPERATIONS

The objectives of this task were to:

a. Develop manufacturing plan.

b. Manufacture test tank and associated hardware, including multi-purpose test fixture.

Initially two test gores were stretch formed, establishing the optimum width and length for the production gore blanks as 94 cm (37 in.) × 366 cm (144 in.). The maximum elongation measured was 8.4 percent in a 10-inch gauge length and 4.8 percent average over the total length. At the same time, the Loft department prepared the necessary mold lines for the chem-mill etch templates, the gore trim templates, and the support bracket machining and weld fixture tooling.

The Tool department then developed the girth weld tooling, the bulkhead sizing fixture, and tool designs for machining the door and ring, and for holding the brackets during welding. Table 7-1 lists all the tools designed or modified to fabricate the test tank.

The two initial stretch-formed test gores were trimmed, aged, chemically milled to a constant 0.127 cm (0.050 in.) thickness, and butt welded together on the production bulkhead weld fixture, to develop a certified weld schedule. This weld schedule is presented in Figure 7-1. Two cap blanks and thirty-six gore blanks, were successfully stretch formed, trimmed, and aged to the -T87 condition. The gore stretch-forming operation is shown in Figure 7-2 and the cap forming is shown in Figure 7-3. Six additional cap blanks were formed for cap-to-gore weld schedule development. Three pieces were sized to represent the bulkhead and three sized to represent the cap.

Chem-milling etch templates were developed to define both the internal and external patterns for the stiffeners, support pads, weld lands, and transition steps. These templates are shown in Figure 7-4. The template contours were developed from the existing bulkhead plaster master as shown in Figure 7-5. The basic lines for the complete gore patterns were originally layed out on this master and transferred to the templates. Gore thickness was accounted for by an appropriate build-up on the plaster master. One set of templates was used for both the forward and aft bulkhead gores, since the only difference between these gore patters was the support fitting pads, which appear on the aft bulkhead only.

Table 7-1. LWT tank tool list.

Part Number	Tooling Symbol	Description
PD75-0120-500	HOFX	Major Tank Girth Weld Fixture
PD75-0120-500	WLFX	Bulkhead Perimeter Sizing Tool
55-72728-570	WLFX	Bulkhead Cap/Ring Weld Fixture
7-73101-574	WLFX	Bulkhead Gore Butt Weld Fixture
55-72320-570	PLMS	Centaur Master Bulkhead Plaster Master
57-72105-75	STFM	Centaur Bulkhead Gore Stretch Form
PD75-0121-1	MCAC	Gore Stretch Measuring Tool
PD75-0121-1	PLMS	Gore Chem-mill Etch Pattern
55-72728-570	TOAC	Centaur Bulkhead Cap Weld Fixture
PD75-0125-1	TCPA	Tank Bracket Profile Template
PD75-0125-1	PFFX	Tank Bracket Holding Fixture
PD75-0125-1	DRPE	Tank Bracket Drill Fixture
PD75-0125-1	PLMS	Tank Bracket Contour Template
PD75-0122-1	TUFX	Door Turning Fixture
PD75-0122-1	TCTP	Door Trace Template
PD75-0123-1	TRTP	Gore Trim Template, Net
PD75-0123-1	ETTP	Gore Exterior Etch Template
PD75-0123-1	ETTP	Gore Interior Etch Template
PD75-0122-1	TCTP	Door Inside Radius Trace Template
PD75-0123-500	CKTP	Gore Contour Check Template
PD75-0123-501	CKTP	Gore Girth Radius Check Template

INERT-GAS, MACHINE WELDING SCHEDULE E 629286 | MACHINE NO. 65 | DATE 2/25/76

MATERIALS	GAUGE	P. C. NO.	TEST DATA	X-RAY NO.
2219 T-87 ALUMINUM ALLOY	.050	3E387		2X6079

CURRENT SUPPLY CONTROL: STD. RANGE: 12-180
CURRENT RHEOSTAT: NA START ADJ: NA
CONTACTOR: REMOTE POLARITY: STRAIGHT
HI FREQ: START X CONT. OFF RHEOSTAT: NA
CURRENT RHEOSTAT: 35 AMP. METER: 65
RAM TRAVEL-RANGE: 0-3000 DIAL: 2.3 IPM: 14
ELECTRODE MAT'L: W 2% TH DIA: 3/32" SHAPE: BLUNT
NOZZLE NO: AIRCO CHROME I.D: .55"
GAS LENS: NA TRAILING CUP: NA
BACK-UP BAR MAT'L: STAINLESS TEMP: AMBIENT
GROOVE WIDTH: .187 CLAMP PRESSURE: 40 LBS.
ARC VOLTAGE POWER: PANEL START DELAY-SEC: - 0 -
ARC POTENTIAL-VOLTS: 14.20 METER: 14
ELECTRODE POSITION-INCHES: .030"
WIRE FEED POWER: PANEL START DELAY-SEC: -0-
SPEED: METER: 10 IPM: 10 STOP DELAY-SEC: -0-
ARC OSCIL. FREQ. NA AMPL. NA POSIT. NA DWELL. NA
TORCH GAS: HELIUM 45 CFH ARGON - CFH
BACK-UP GAS: HELIUM 5 CFH ARGON - CFH

SPECIMEN NO.	DIMENSIONS			ULTIMATE STRENGTH	
	THICKNESS	WIDTH	AREA	POUNDS	PSI
1	.050	.500	.025	1035	41400
2	.050	.498	.025	1025	41000
3	.050	.504	.025	1050	42000
4					
5					
6					

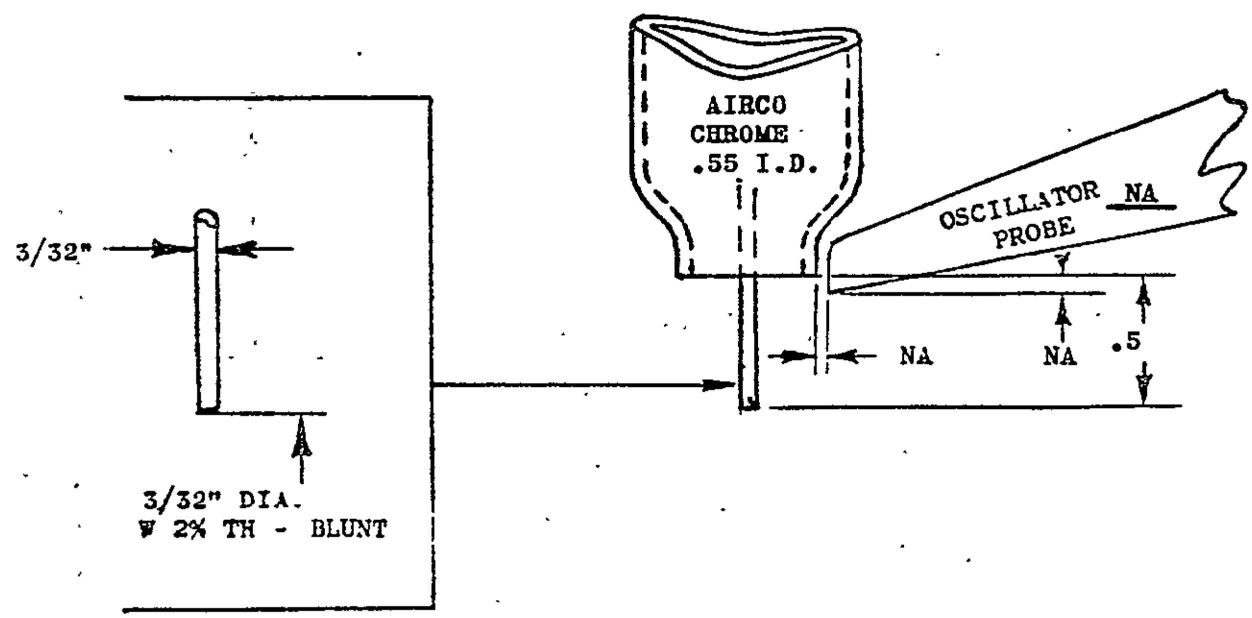
AVERAGE PSI 41,467 | MINIMUM REQ. 35,000

CLEAN. PER: 1-02573 DRAWFILE EDGES/HAND SCRAPE ¼" FROM EACH EDGE.

WELDING ENGINEER SIG.	PROCESS CONTROL SIG.	STRUCTURAL ENGINEER SIG.
Milwaukee 632-1	W. Hageman	

SPECIAL INSTRUCTIONS
PROGRAM: PD 75-0120 LIGHTWEIGHT TANK ASSEMBLY.

FILLER MAT'L: 2319 1/16"DIA.



A1103-4 3/74

Figure 7-1. Inert-gas, machine welding schedule.

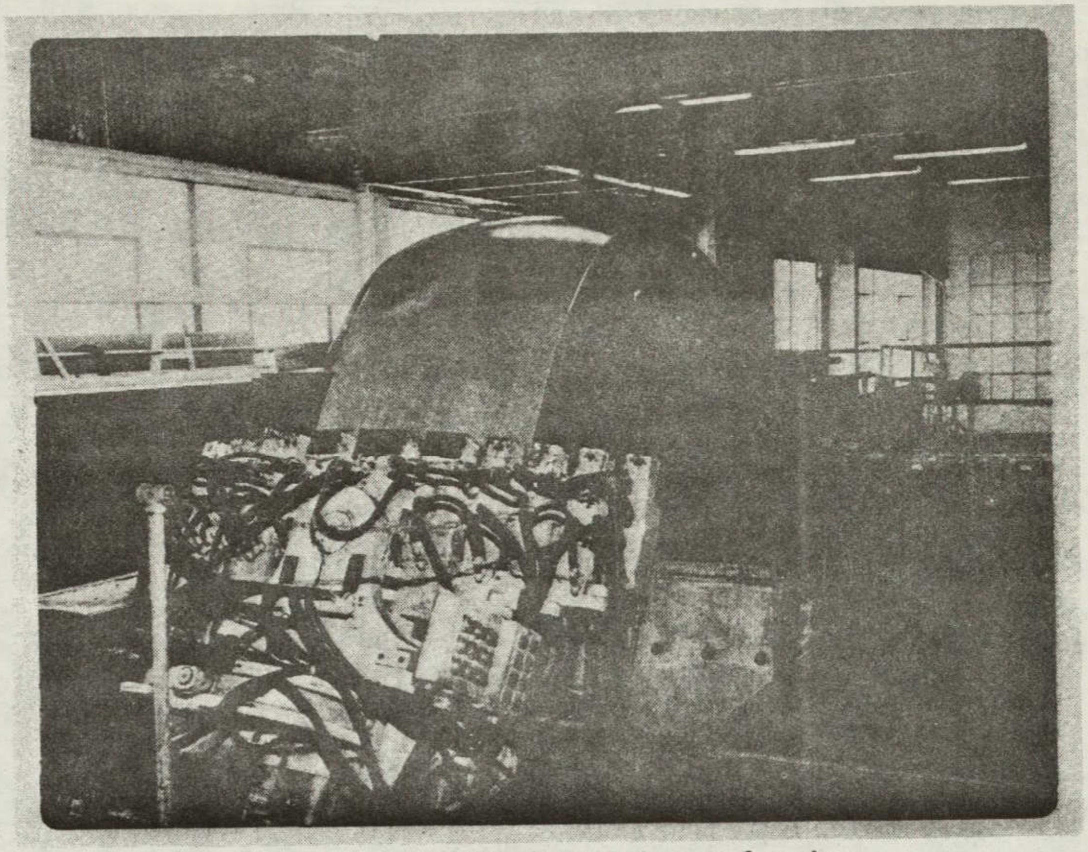


Figure 7-2. Lightweight tank gore forming.

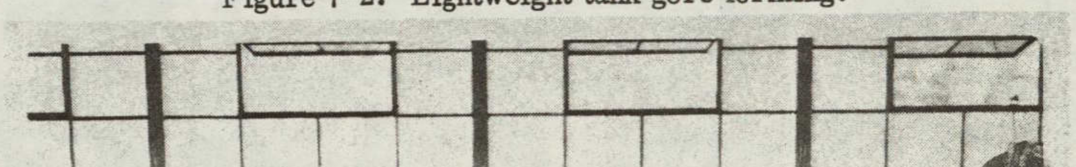


Figure 7-3. Lightweight tank cap forming.

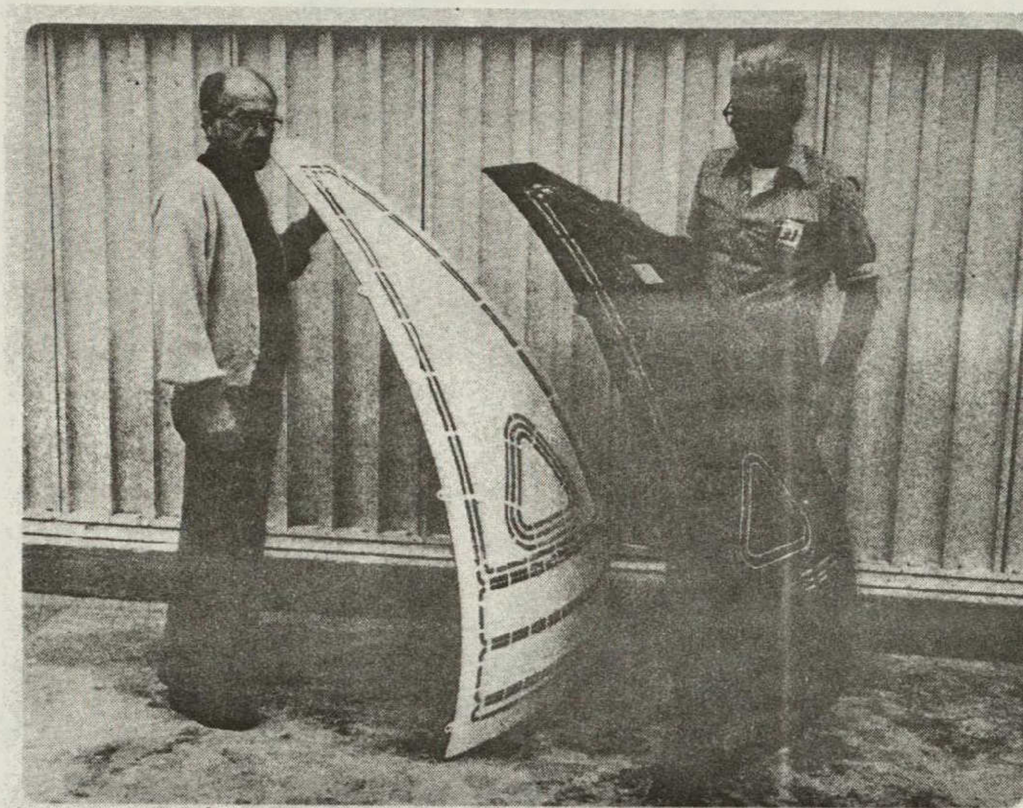


Figure 7-4. Lightweight tank gore chem-milling etch templates.

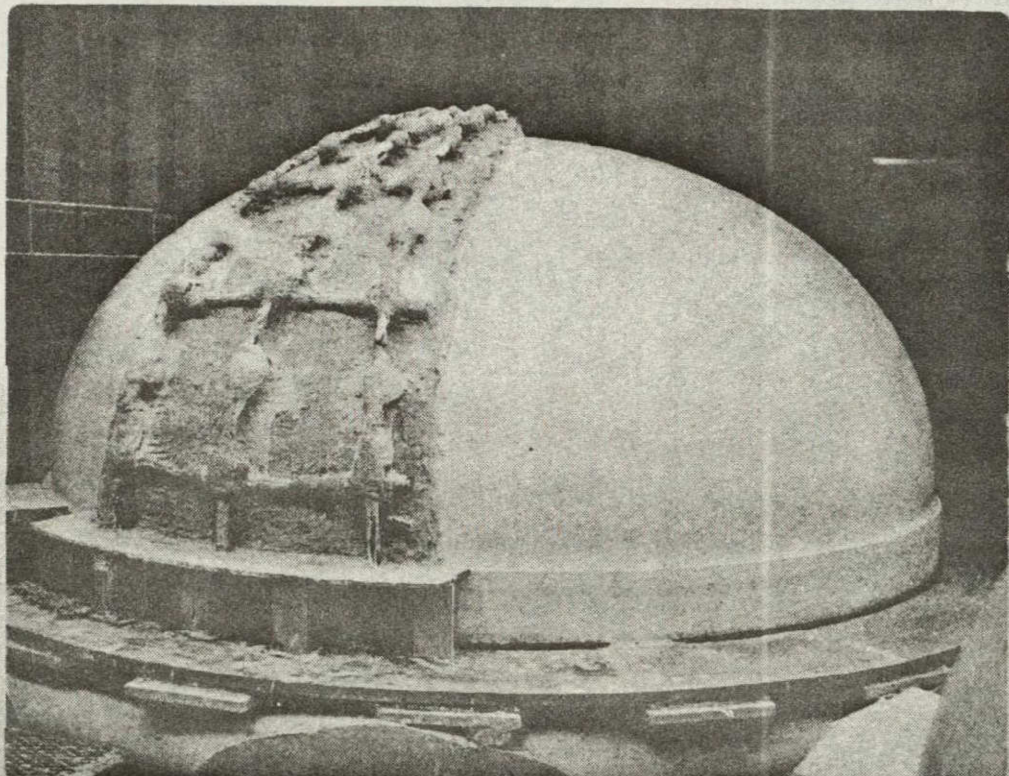


Figure 7-5. Centaur bulkhead plaster master.

The basic gores, caps, and etch templates were shipped to Chemical Energy of California for chem-milling. Since the cap piece etch pattern fundamentally consists of concentric circles, and only two pieces were to be fabricated, the etch pattern was layed out by the vendor by hand on each part.

The initial stretch forming operation produced a thickness variation of 0.020 cm (0.008 in.) in the gore blanks. Since the total tolerance allowed on the finished chem-milled gore was ±0.013 cm (0.005 in.), a preliminary sizing operation was required to bring the gore blanks into an acceptable variation level before pattern chem-milling.

The two upper bulkhead cap sections (PD 75-0123-3) were chem-milled and accepted. Some of the gore sections (PD 75-0123-1 and -2) developed varying degrees of surface pitting. After reviewing the completed parts and the processing procedures the Materials and Process department drew the following conclusions:

a. The pitting condition is believed to have been caused by an unknown processing condition which was temporarily out of control, such as solution chemistry, solution temperature, solution agitation, part immersion, part agitation, precleaning, post rinsing, etc. The adverse processing condition apparently has now been corrected.

b. The specific process variable(s) which caused the pitting is unknown, but is believed to be related to a gassing reaction during chem-milling. The initial sizing operation is particularly suspect since some changes to the normal chemical milling operations were made to reduce the metal removal rate.

c. There is no evidence that material quality contributed to the pitting condition. However, several chemical milling sources have reported that 2219 aluminum alloy is more susceptible (i.e., sensitive) to preferential attack, due to processing variations, than most other aluminum alloys that are chem-milled.

Seven aft gores and two forward gores were rejected. The total quantities of forward and aft configurations chem-milled were revised to cover the larger quantity of aft gore rejects.

The Centaur bulkhead gore-to-gore weld fixture was modified to weld the aluminum gores instead of the Centaur stainless steel gores. Figure 7-6 shows the overall weld fixture and Figure 7-7 shows the TIG welding head. As the gores were assembled they were fit-checked on the sizing tool shown in Figures 7-8 and 7-9. The final gores were trimmed to fit the dimension derived from this tool, to assure that both bulkheads had identical girth dimensions.

Twenty-four (PD 75-0125) support brackets were machined and fitted with spherical bearing asebmlies prior to welding the brackets to the aft bulkhead subassembly. The other machined parts were the door, outlet boss, and door ring, shown in Figures 7-10, 7-11, and 7-12, respectively. The formed dome cap piece was machined to fit the

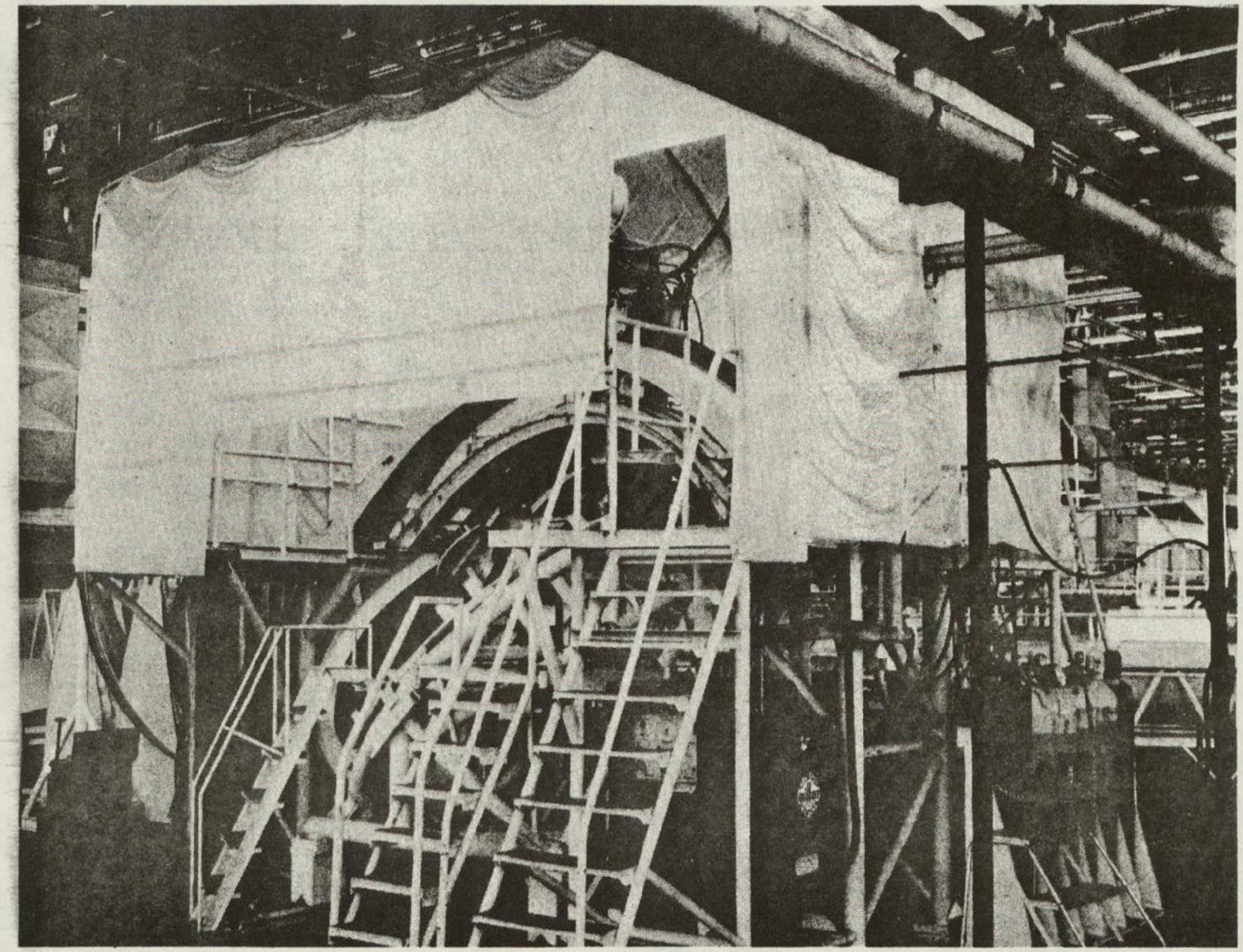


Figure 7-6. Centaur bulkhead weld fixture.

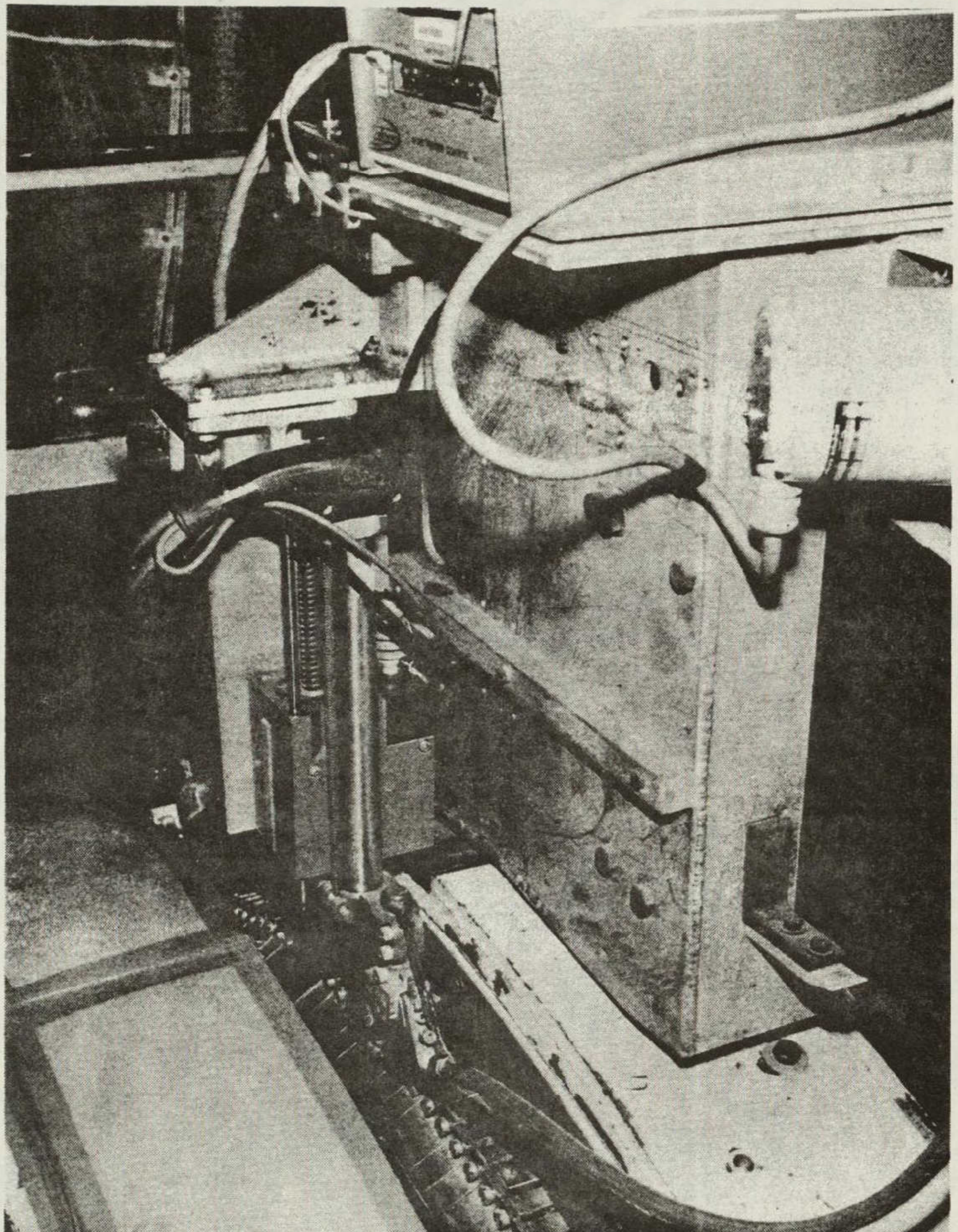


Figure 7-7. Gore welding head.

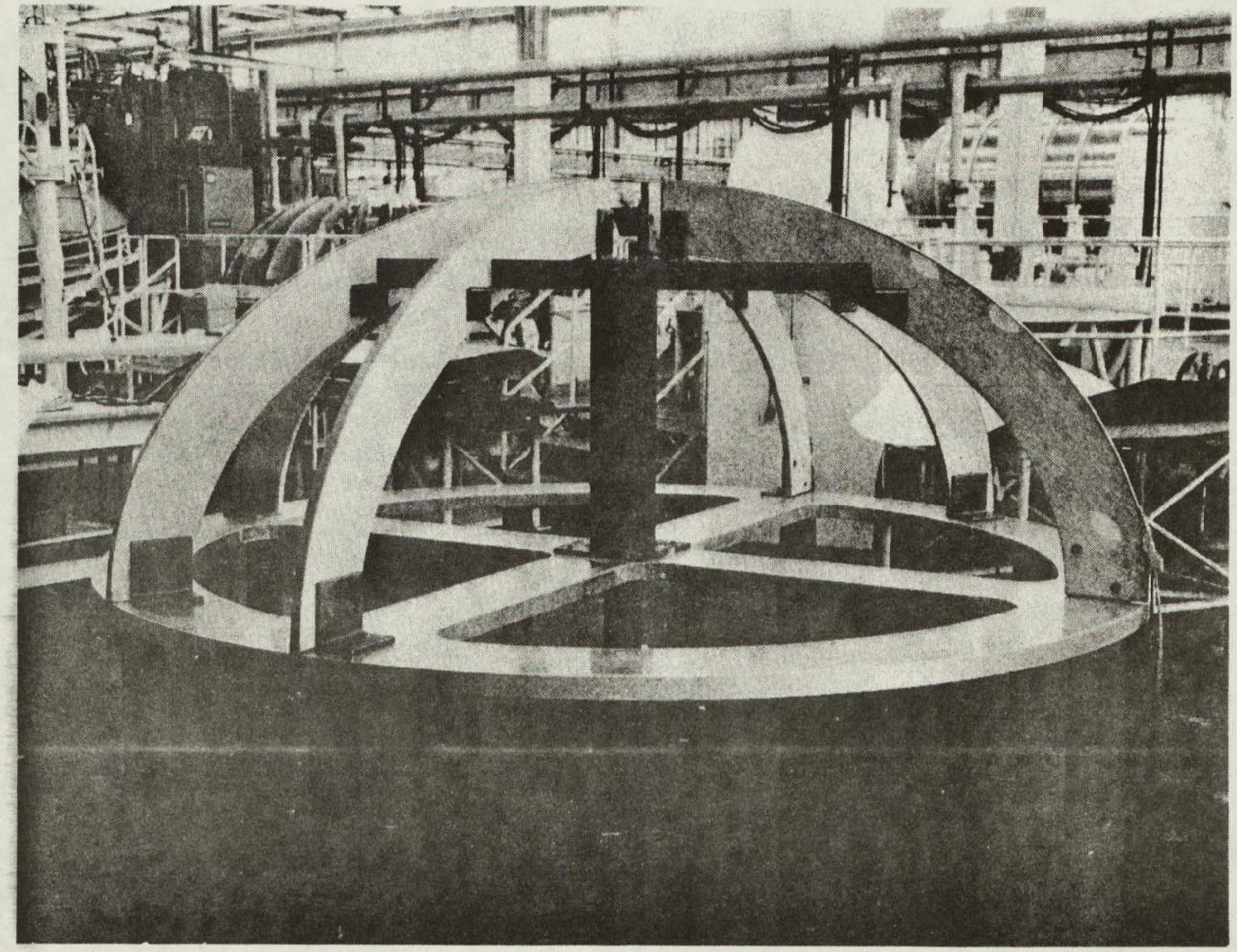


Figure 7-8. Bulkhead sizing tool.

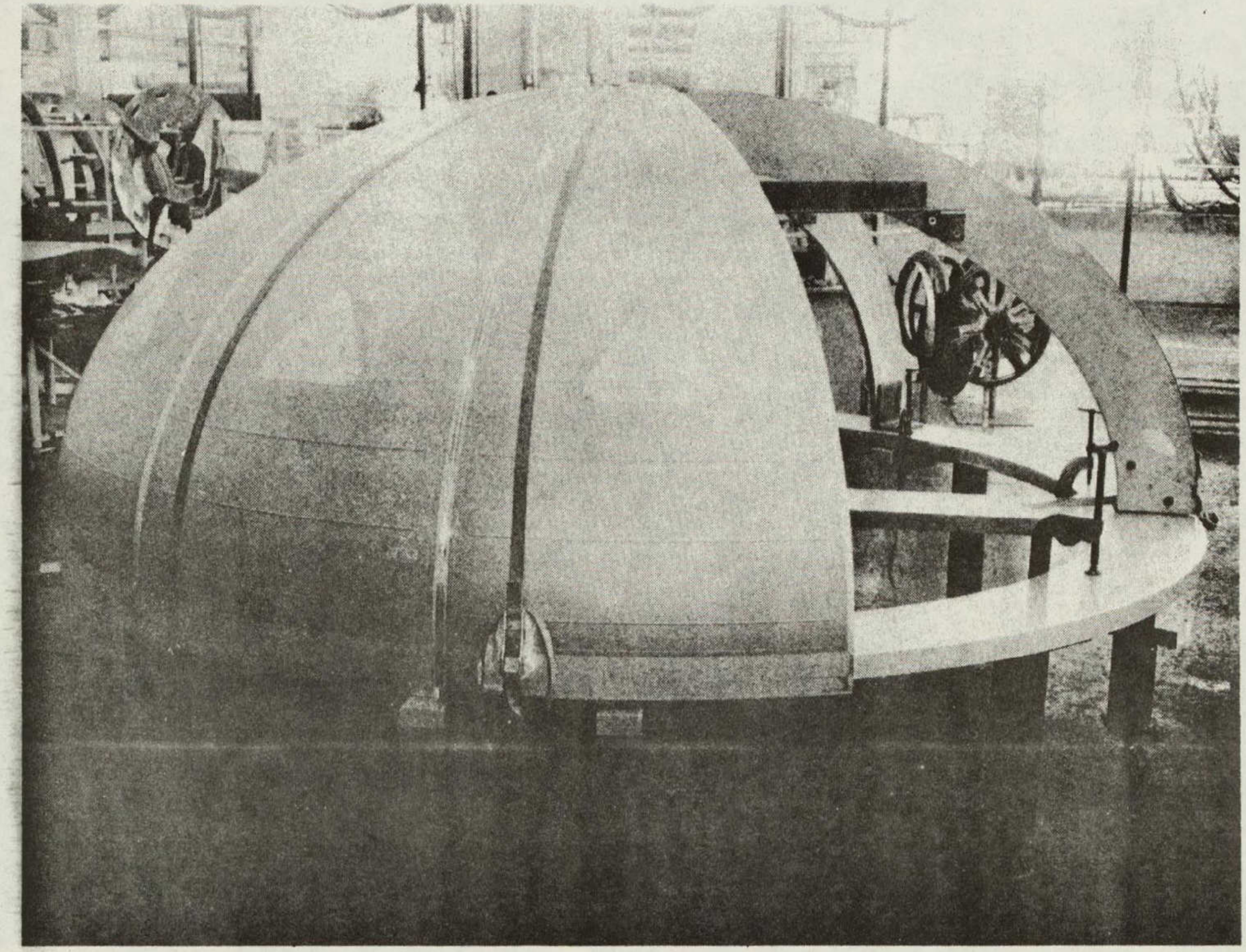


Figure 7-9. Aft bulkhead gores on sizing fixture.

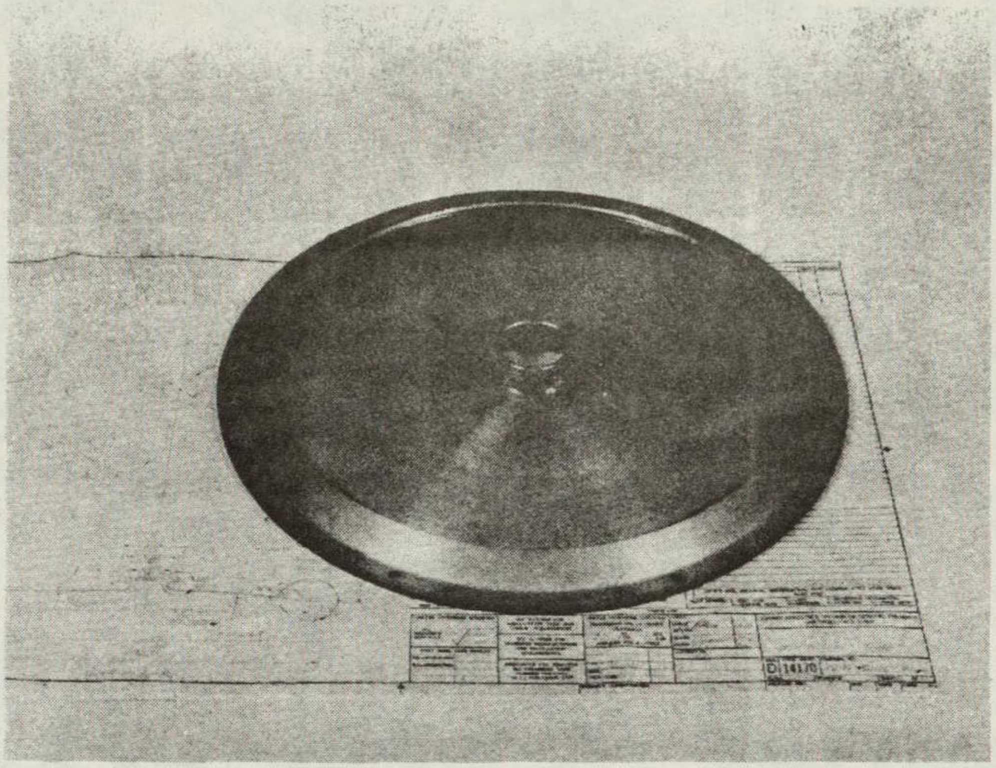


Figure 7-10. Tank door.

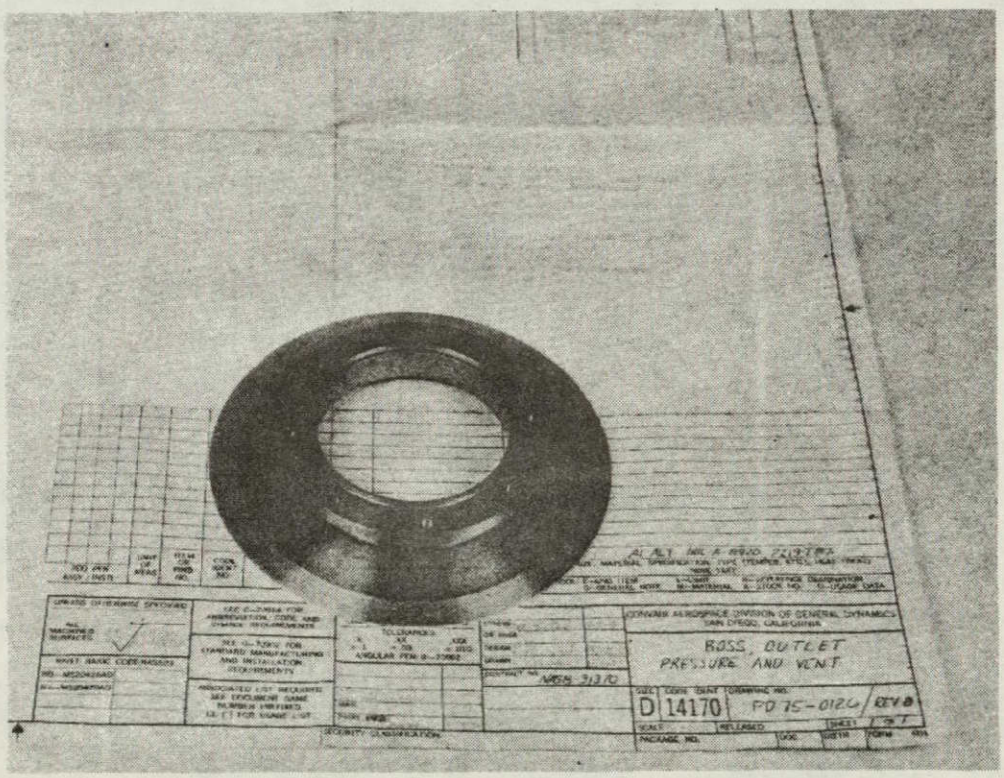


Figure 7-11. Tank outlet boss.

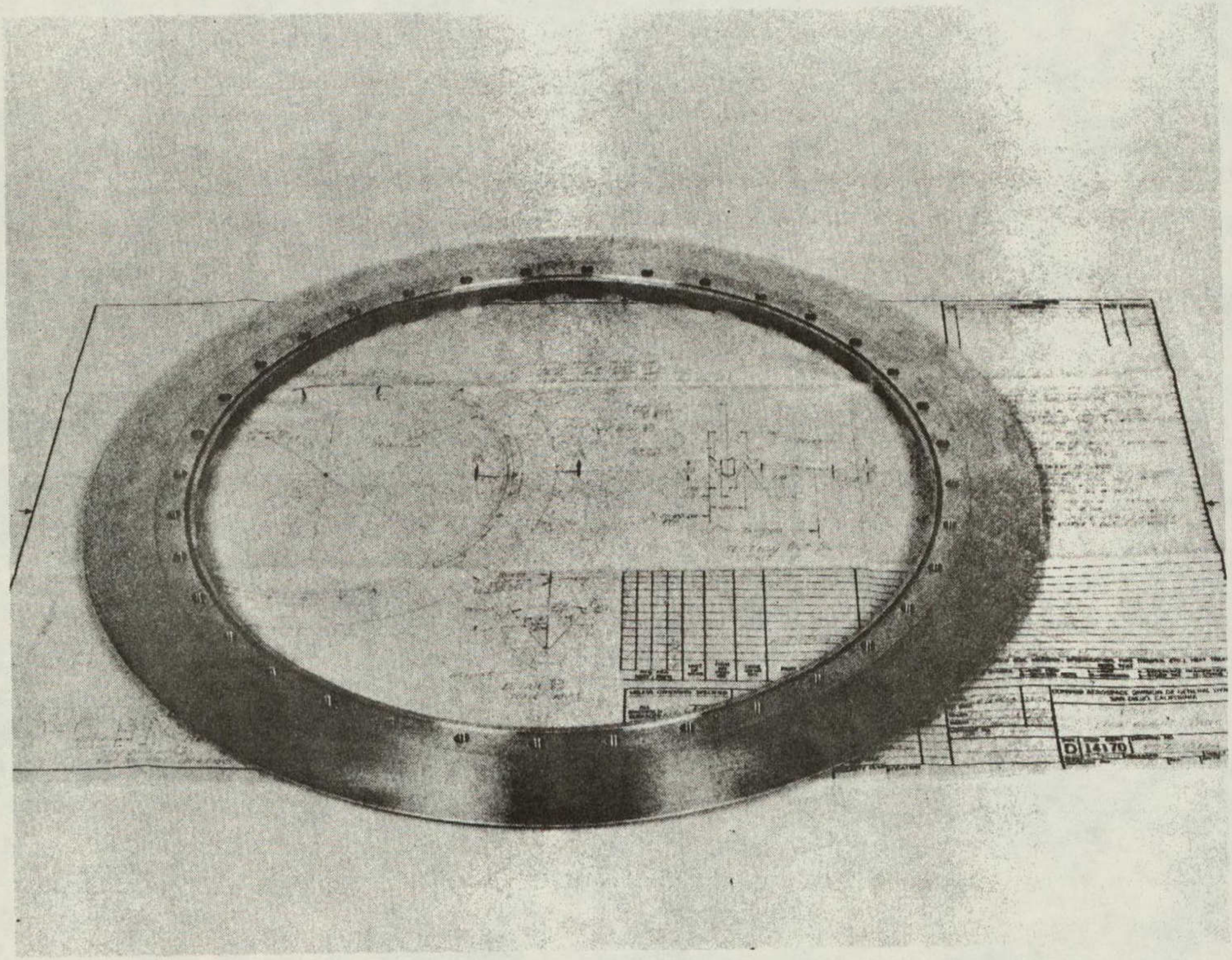


Figure 7-12. Lightweight tank door ring.

forward bulkhead opening and the outlet boss diameter. This part is shown in Figure 7-13. Table 7-2 lists the actual weights of the completed detail parts.

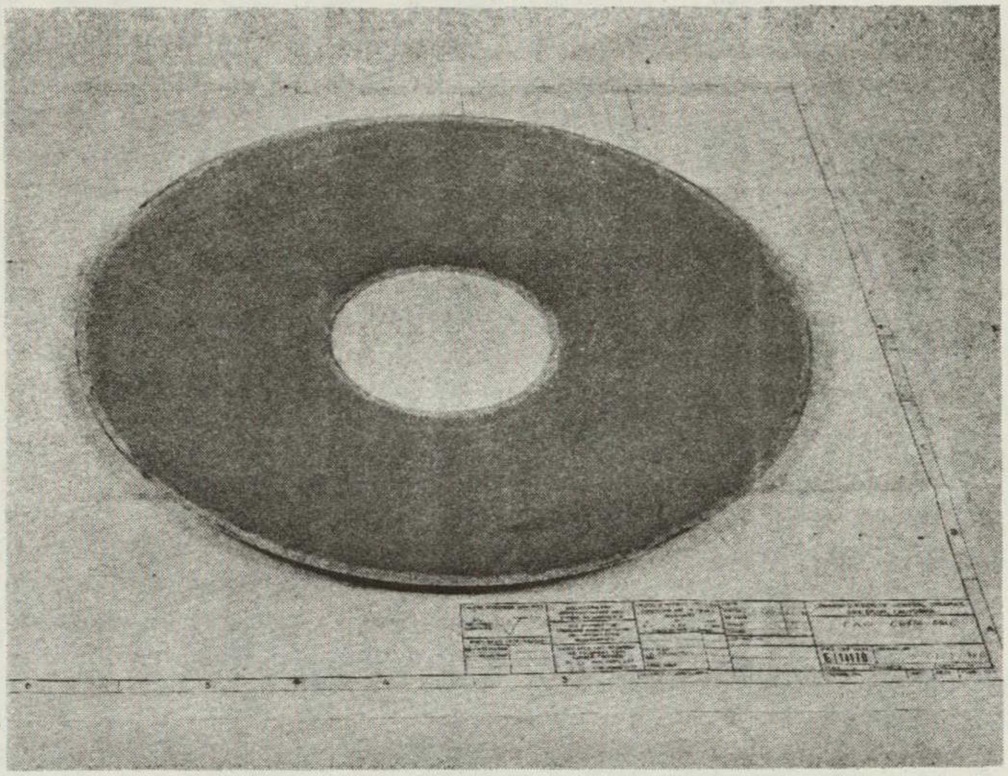


Figure 7-13. Tank dome cap.

Table 7-2. Detail part weights (actual).

Part No.	Name	Quantity	Weight, Kg (lb)
PD75-0122-1	Door	1	3.77 (8.32)
PD75-0123-1	Aft gore	12	2.93 (6.47)
PD75-0123-2	Fwd gore	12	2.52 (5.57)
PD75-0123-3	Cap	1	0.79 (1.74)
PD75-0124	Door Ring	1	2.42 (5.34)
PD75-0125	Bracket	24	0.03 (0.075)
PD75-0126	Outlet	1	0.38 (0.84)

Each bulkhead was subassembled as twelve gore weldments. The forward bulkhead was completed first, then the forward and aft bulkheads were mated/sized before performing the final gore weld on the aft bulkhead. Figure 7-14 shows this bulkhead-to-bulkhead sizing operation. The forward bulkhead was placed in the Centaur bulkhead "Salad bowl" trim fixture and the aft bulkhead was aligned to the forward bulkhead using a clamp-type shop aid. The girth skirt on each bulkhead had been rough trimmed to within 1.25 cm (0.5 in.) of the net EOP prior to clamping the bulkheads together. The final trim line for the gore close-out weld on the aft bulkhead was then scribed and the gores were trimmed, fitted, and successfully welded.

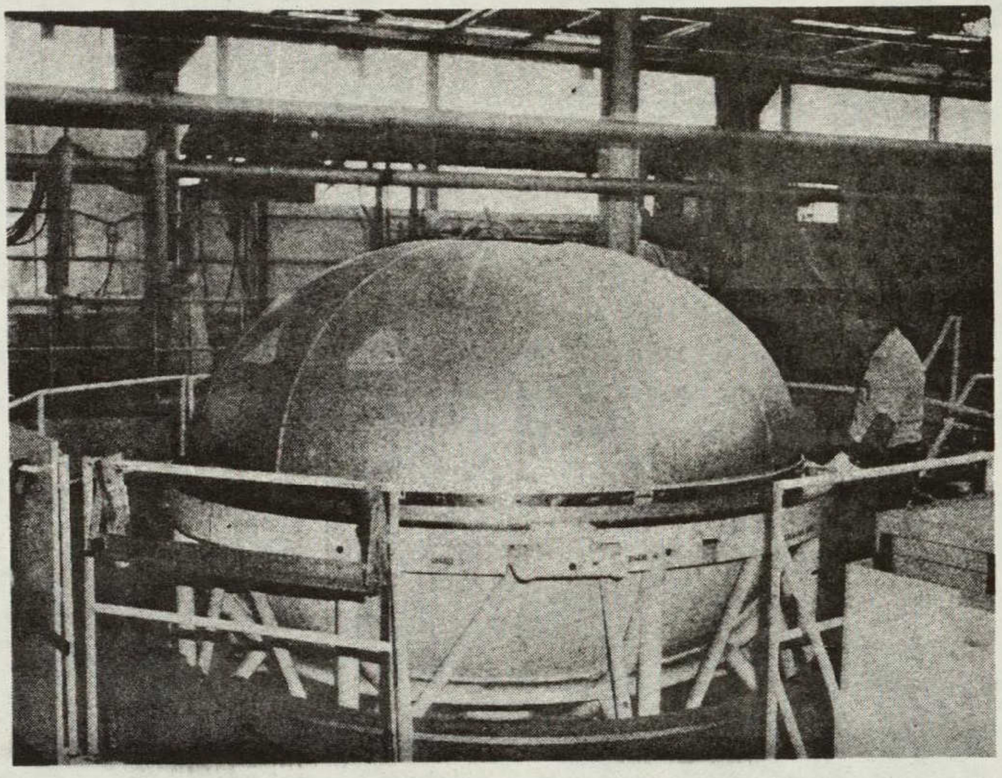


Figure 7-14. Bulkhead-to-bulkhead sizing.

The outlet boss and dome cap were welded together as a subassembly. The hole in the cap piece was cut 0.076 cm (0.030 in.) smaller in diameter than the mating boss, to allow a liquid nitrogen shrink fit preassembly for welding. The maximum contraction of the boss was calculated to be 0.080 cm (0.0314 in.). The developed weld schedule is presented in Table 7-3 and the tensile weld test specimen results are:

Specimen Number	Ultimate Stress N/cm^2 (KSI)
1	2.98×10^4 (43.2)
2	2.90×10^4 (42.1)
3	2.90×10^4 (42.1)

Table 7-3. Dimetrics programmable TIG-MIG weld schedules.

Material: 2219-T87 Aluminum (Lightweight Tank)
Thickness: 0.050 inch
Wire: 3/64-inch-diameter 2319 Aluminum
Pass: Single

Designation	Parameter	Setting
A	High Pulse KPPS	20.0
B	Initial Current	040
F	Weld Current	110
G	Background Current	050
K	Inverted Background Current	—
J	Inverted Weld Current	—
QI	Pulsed Arc	On
AB	Weld Current Period	150
AC	Background Current Period	075
M	Final Current	010
Q2	Cyclic Polarity	Off
AD	Normal Period	—
AE	Inverted Period	—
B	Prepurge Period	005
C	Initial Period	2.5
E	Initial Slope Period	2.0
H	Weld Period	999
L	Final Slope Period	5.0
N	Final Period	5.0
P	Post-Purge Period	010
R	Start Delay	4.0
S	Wire Feed	35
T	Stop Delay	0.5
Q4	Wire Mode	Program
U	Pullback	0.1
V	Start Delay	1.0
W	Carriage IPM	15 (5.10 on Aronson Pot)
X	Stop Delay	4.5
Y	Start Delay	3.0
Z	Arc Voltage	15 (sample)
AA	Stop Delay	0.1
AF	Arc Start Intensity	0.2

Tungsten: 2% thoriated, 1/8-in. dia., 0.60 truncation × 25° taper
Gas: Helium at 90 CFH No. 10 Cup
Q3: Straight Polarity
Q5: GTA
Weld Spec.: 1-02573 MIL-W-8604
Cleaning: MOS 1-02801-003
Weld Joint: Sq. Butt
Position: Downhand
Interpass Temp: NA
WLFX No.: PD75-0122-1 TUFX

The tooling used to hold these parts for the welding operation is shown in Figure 7-15, the welding operation in Figure 7-16, and the completed weld assembly in Figure 7-17.

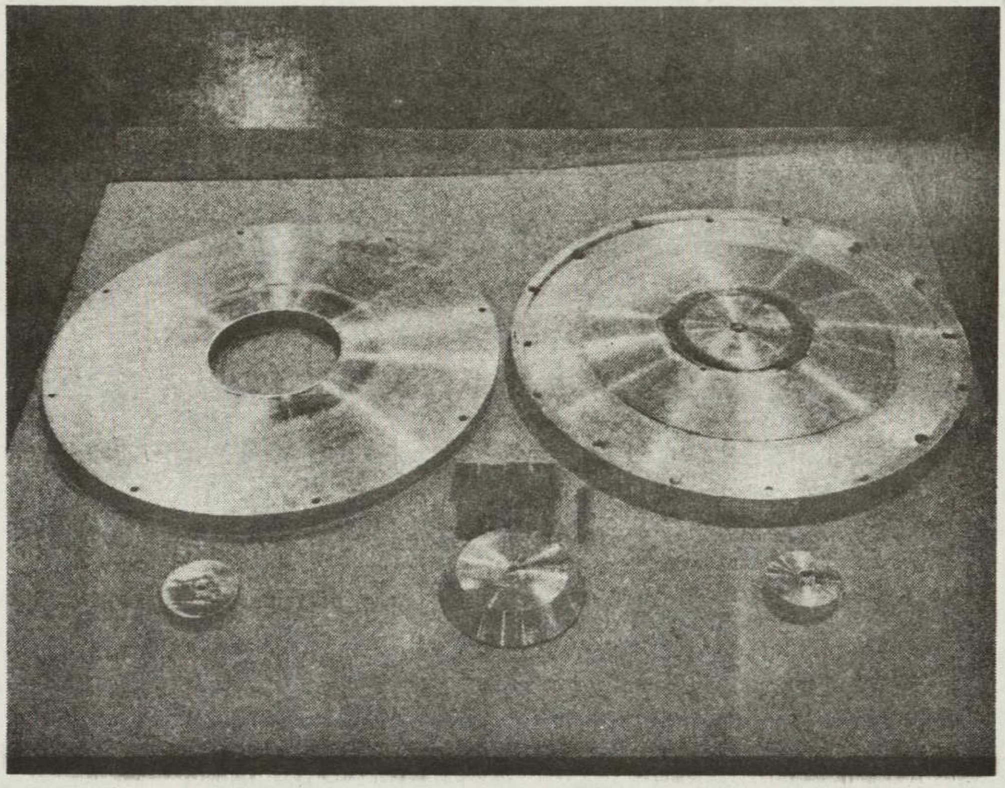


Figure 7-15. Boss-to-cap weld tooling.

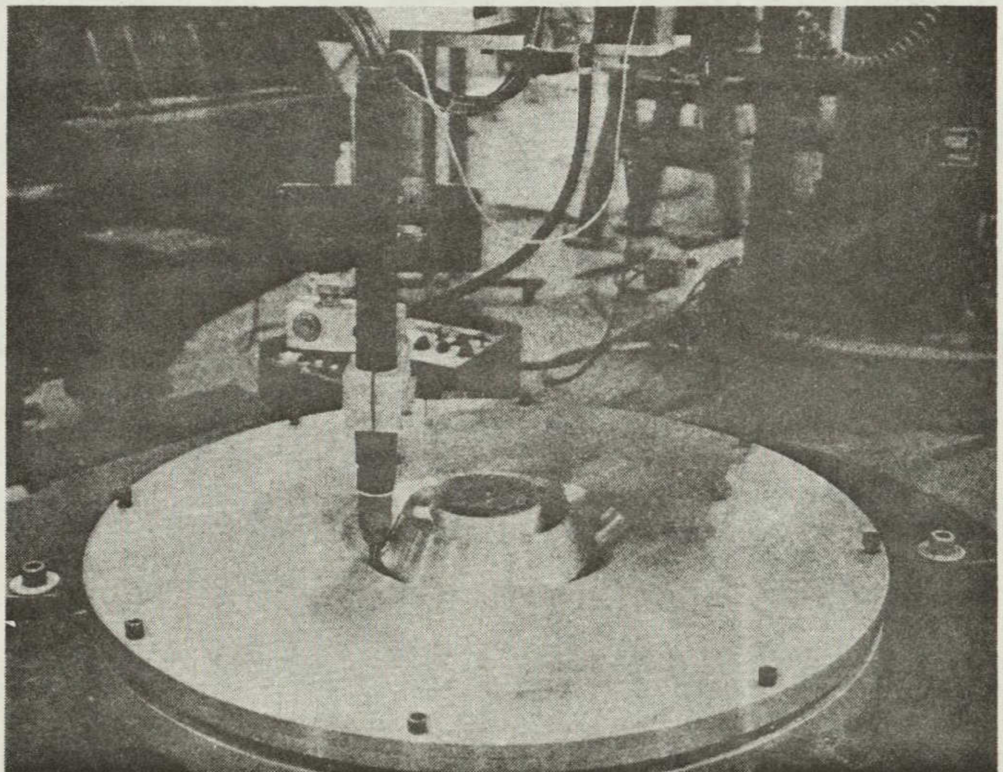


Figure 7-16. Boss-to-cap welding operation.

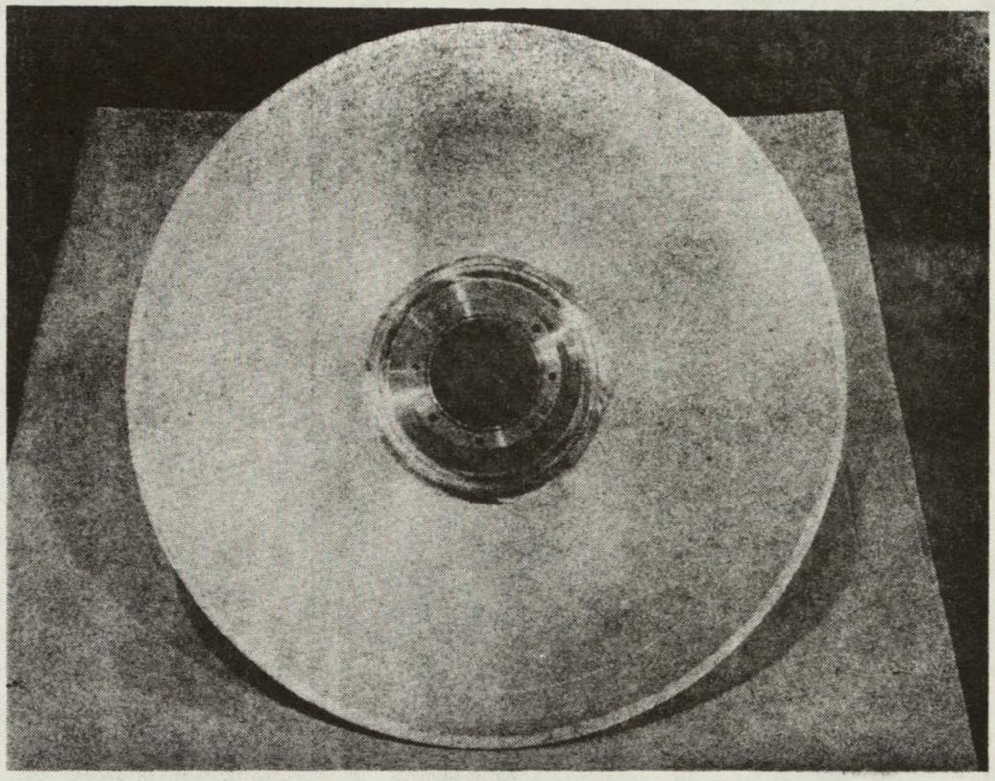


Figure 7-17. Boss-to-cap subassembly.

The Centaur cap welder (Figure 7-18) was fitted with the wire feed system previously used for the bulkhead gore-to-gore welding. The final certified weld schedule is shown in Table 7-4 and the related tensile weld test specimen results are:

Specimen Number	Ultimate Stress N/cm^2 (KSI)
1	3.08×10^4 (44.7)
2	2.78×10^4 (40.3)
3	3.00×10^4 (43.5)

The cap weld backup ring was contoured to accept the elliptical contour of the forward cap and would not properly support the taper of the door ring. The forward bulkhead had to be welded and accepted before modification of the backup ring for welding the door ring to the aft bulkhead. The forward bulkhead cap welding operation is shown in Figures 7-19 and 7-20. The cap weld was completed and accepted, then the bulkhead was net trimmed at the girth in preparation for the girth weld. The backup ring was remachined to fit the door ring and reinstalled in the cap welder. The aft bulkhead was mounted on the cap weld fixture in the same manner as the forward bulkhead. The door ring was welded and the bulkhead girth area trimmed to the net dimensions, similar to the forward bulkhead.

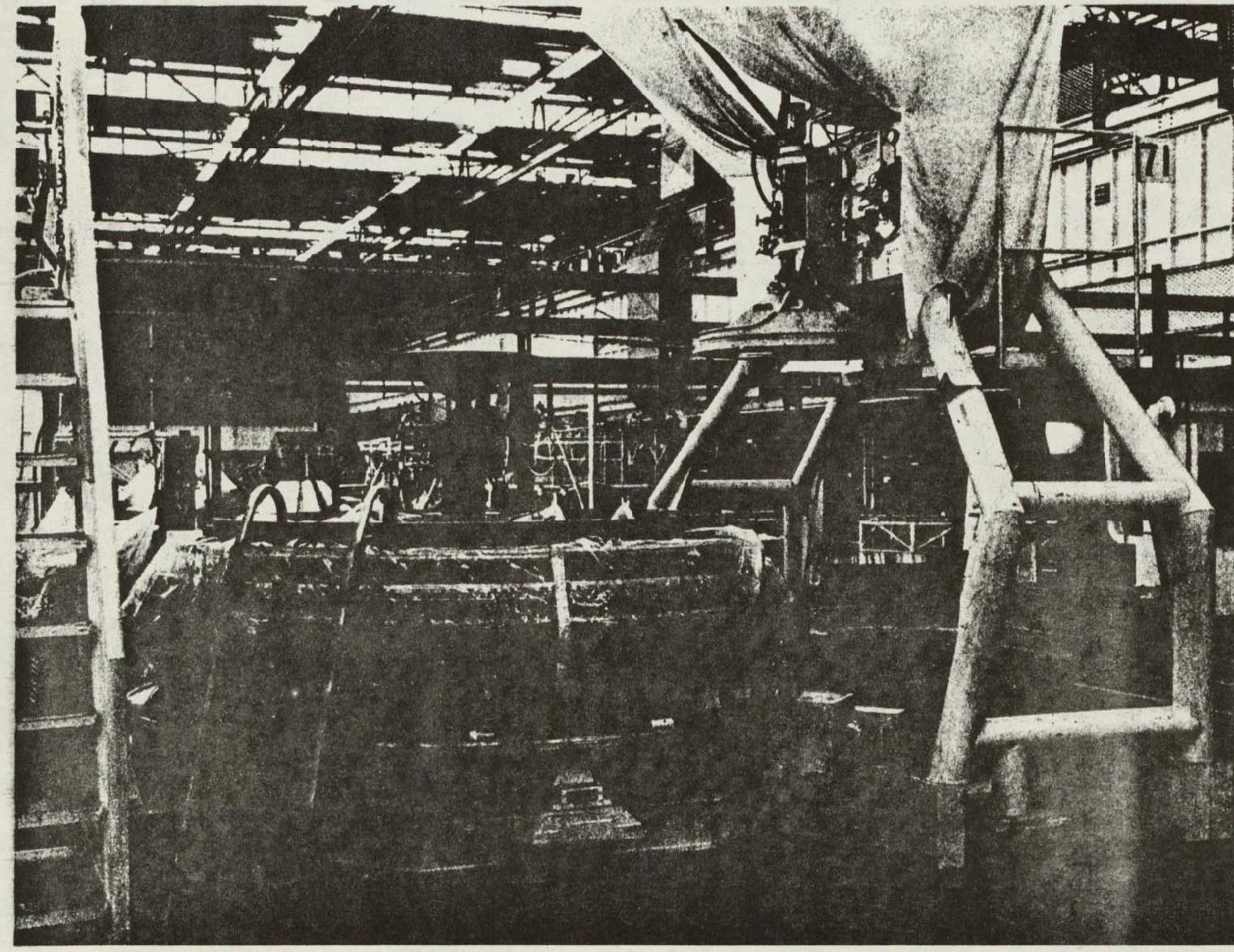


Figure 7-18. Bulkhead cap welding fixture.

Table 7-4. Automatic TIG weld certification.

Machine: Shop No. 71, WLFX 55-72323-570
Power Supply: NASA 803327 (TEKTRAN TR-150)
Application: PD 75-0121 Lightweight Aluminum Tank
Material: 0.050-in. 2219 T-87 Aluminum
Main Console:

Power Supply

Settings:
- Initial Current: 32
- Final Current: 10
- Gas Preflow: 1 sec
- Initial Time: 2 sec
- Slope: 2 sec
- Slope Time: 8 sec
- Final Time: 5 sec
- Post Time: 5 sec
- Test/Weld: Weld
- Start Current: 40.0
- Remote/Program: Remote
- Hi Pulse: Off
- Pulse: On
- On Time: 1.0
- Off Time: 1.7
- Amplitude: 8
- HF Starter: 100%

Meters:
- D.C. Amperes: 52-54
- D.C. Volts: 16.5

Remote Pendant

Settings (Variable):
- Current Control: 3.60
- Sequence Start: Push to initiate
- Sequence Stop: Push to terminate
- Purge: Not required
- Emergency Stop: As required

Meters:
- Welding Voltage: 15.5
- Welding Current: 52-54

Arc Voltage Control:
- Start Delay: 0.2
- Volts: 15.0
- El. Position: 0.20 in.
- Power: Panel

Filler Wire:
- Size: 1/16 in.
- Alloy: 2319
- Speed: 13.0 in.
- I.P.M. Measured: 11-1/2

Weld Fixture Data:

Backup Gas: Helium   Flow Rate: 5 CFH
Weld Speed Setting: 3.40   Actual Weld Speed: 11 IPM
Backup Bar: Copper   Groove Width: 0.200 in.
Holddown Space: 0.325 in.
Outer ring retract pressure: 50 PSI   Down Outer Ring Pressure: 90 PSI
Inside Bell Ring Pressure: 30 PSI   Down Bell Ring Pressure: 90 PSI

(The outer ring retract and inside bell ring pressure settings are for setup only. Reduce to 0 psi for welding.)

NOTES:
1. Torch Gas: Helium, 35 CFH
2. Electrode: 3/32 in. Dia., W 2% TH
3. Tack Weld: 1 in. every 6 in. manually.
4. D/P: Per B/P and QVP 800.31
5. Clean Per: Hand scrape abutting edges and 1/2 in. back.
6. Start and routine test waived in favor of visual and X-ray inspection due to tool access.

COMMENTS: Wire Feed Control Accessories:
CELESCO MD1-WF-250; CELESCO Panel Model II

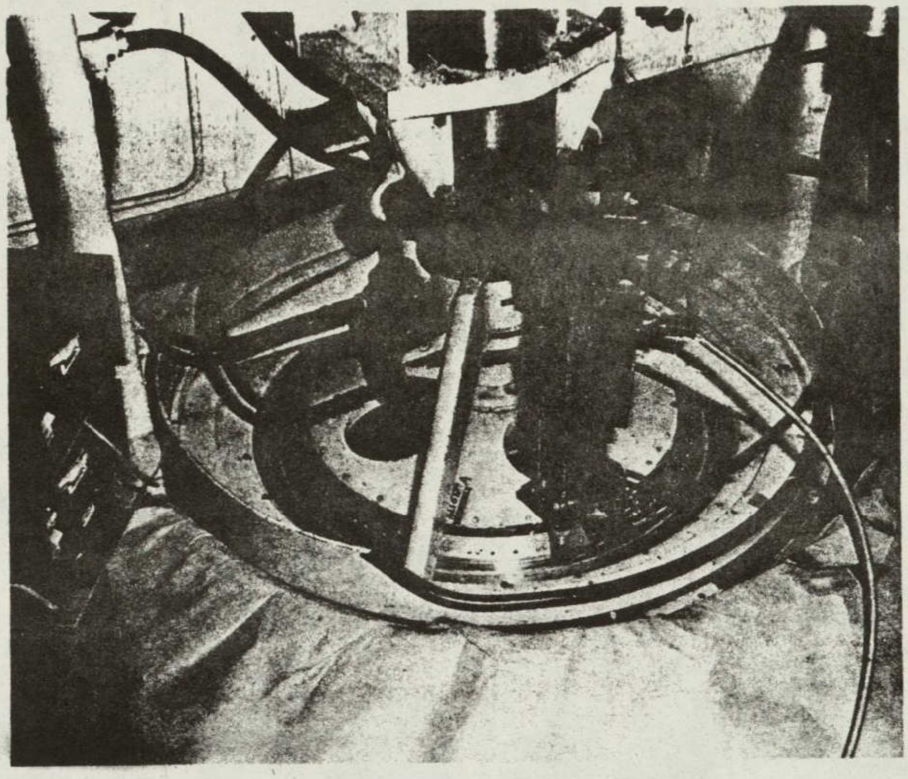


Figure 7-19. Forward bulkhead cap welding operation.

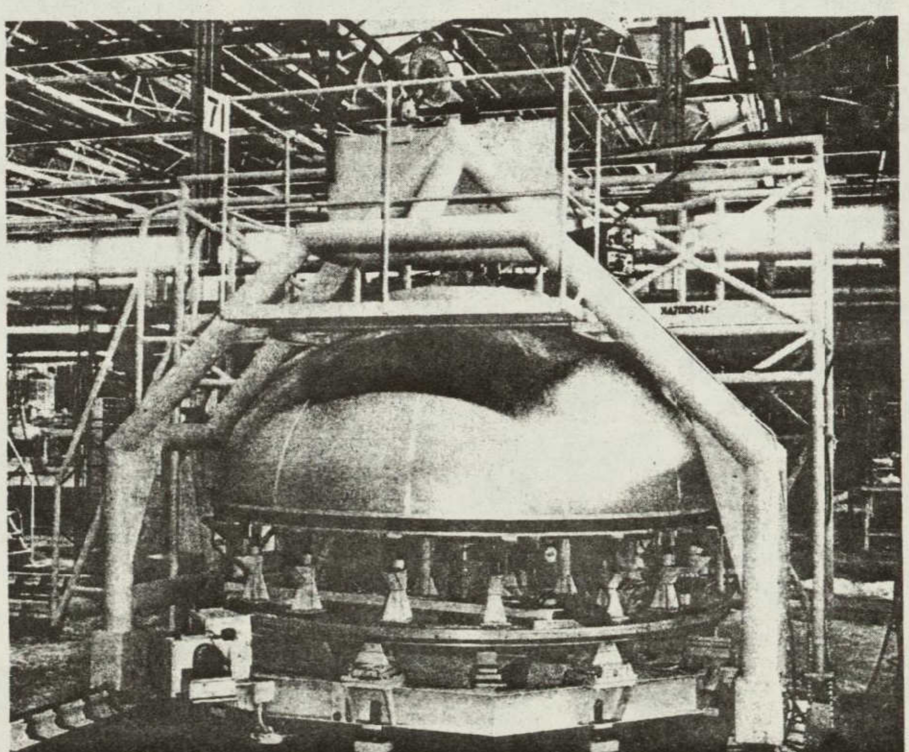


Figure 7-20. Forward bulkhead in cap welding fixture.

Simulated brackets and bulkhead weldment pads (6 sets) were prepared for use in developing weld techniques for the tank support bracket welding operations. These simulation parts were welded and X-rayed. The required weld technique was developed and characteristic X-rays have been produced for comparison to production welds.

Both bulkheads were transferred from USAF Plant 19 to the Kearny Mesa Plant for bracket installation and girth welding. Welded areas on the forward bulkhead were given a hand alodine treatment. The aft bulkhead was positioned on a tooling table and the required centerlines of the bracket pairs determined. The centerlines of the bracket pairs must line up with the centerlines of the support fixture attachment brackets. The centerlines of the bracket weld pads were determined and the bulkhead rotated to bring the bracket-pair and pad centerlines as nearly coincident as possible. Due primarily to gore repair welding, the final gore had to be oversized to close the bulkhead assembly at the required diameter. This circumstance offset the pad centerlines from equal $\pi/6$ radian angles. The offset error was adjusted between pads during the bracket location layout, to minimize the total effect.

The local pads were prepared for welding by hand scraping. The tool used for fabricating the detail brackets was modified and used to locate and position the brackets for welding. Figures 7-21 and 7-22 show this tool and brackets positioned on the bulkhead.

The first set of brackets was welded and weld distortion was obvious on both sides of the pad. It was determined that the bulkhead was moving away from the heat sink during welding. A modification was made to the tool holddown system to increase the clamping capability.

The second pair of brackets was welded but distortion appeared again (though somewhat less). A rigid backup tool was fabricated, using the bulkhead sizing fixture as a foundation, with an internal heat sink backup pad contoured for maximum bulkhead contact and an external screw clamp to hold the bracket firmly in place during welding. The welding fixture and setup is shown in Figures 7-23, 7-24, and 7-25. The welding procedure was modified to weld a single edge at a time, letting it cool until it was cool to the touch before welding the next edge. With the new tool and weld procedure, the remaining twenty brackets were welded without any perceptible distortion. Figure 7-26 shows the completed aft bulkhead.

The excess material cut off the bulkheads during trimming at the girth provided two complete bands. These bands were used to simulate the bulkheads on the girth weld fixture. The complete girth welding fixture setup is shown in Figure 7-27. The bulkhead bands were positioned on the backup wheel and a high speed router, mounted normal to the wheel, was used to perform the final trim of the band edges for a good line fit. The bands were then welded under simulated bulkhead-to-bulkhead welding conditions.

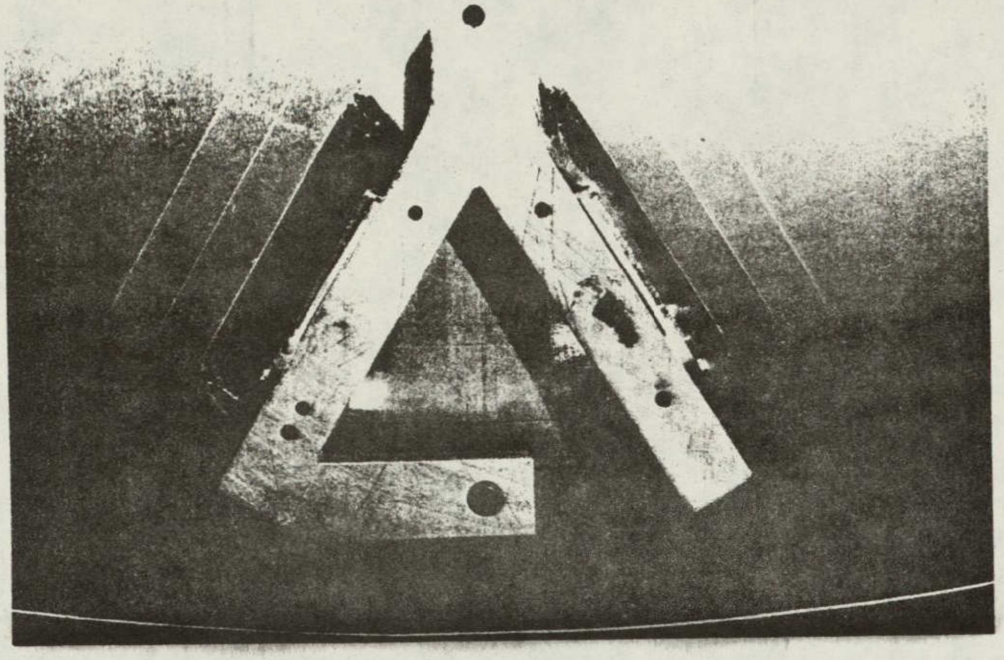


Figure 7-21. Pair of brackets with locating tool positioned on bulkhead.

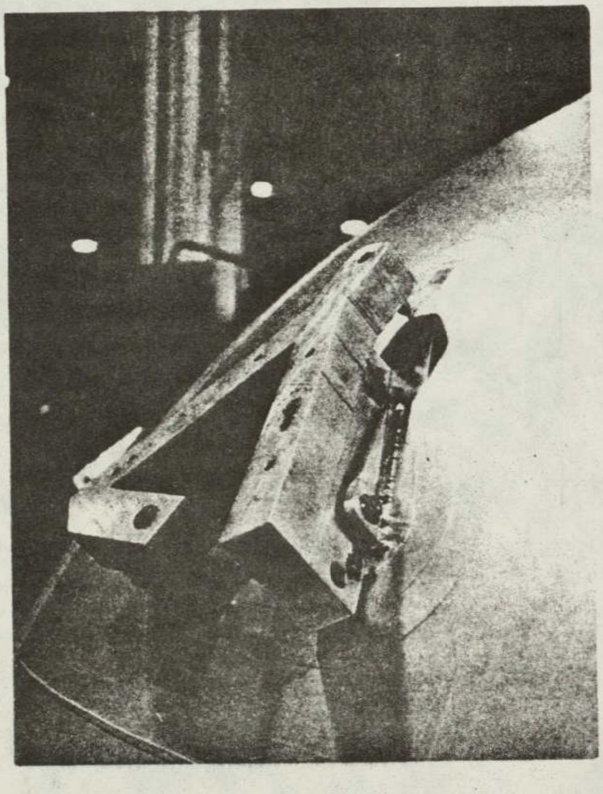


Figure 7-22. Welded bracket with alignment tool.

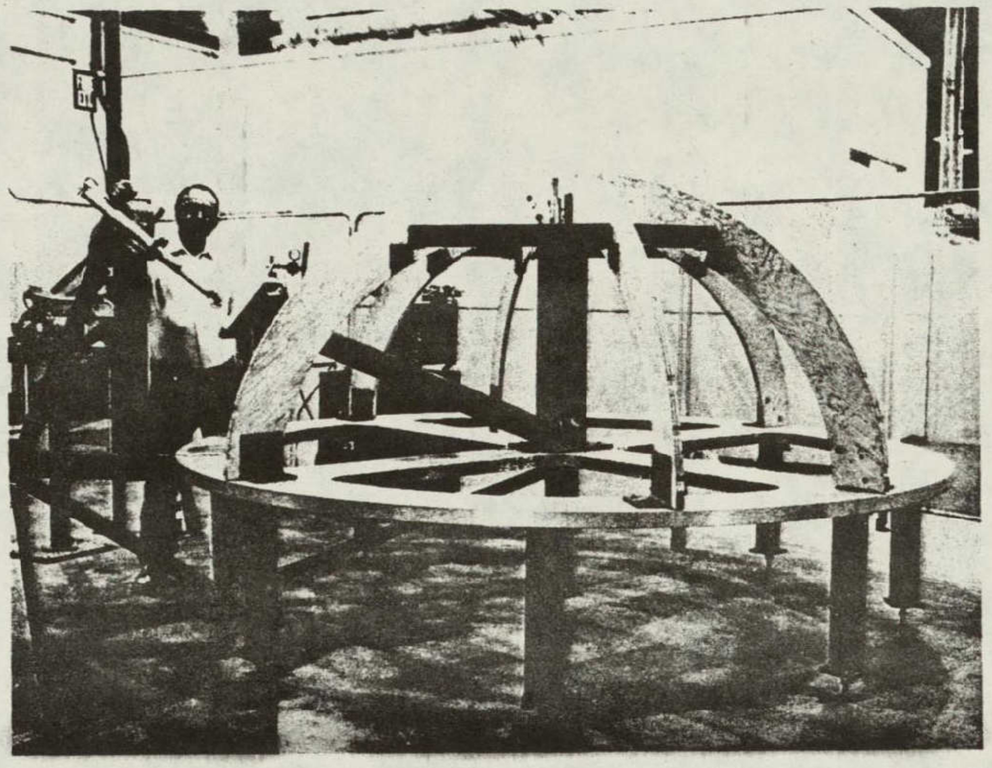


Figure 7-23. Sizing fixture modification for bracket welding.

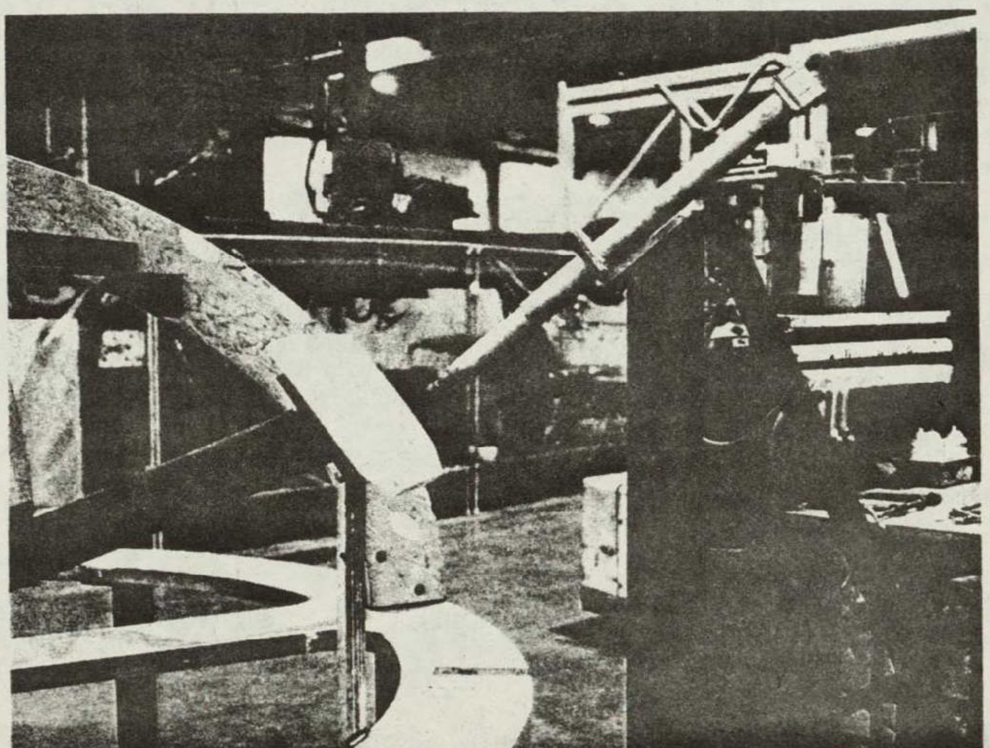


Figure 7-24. Bracket clamping fixture.

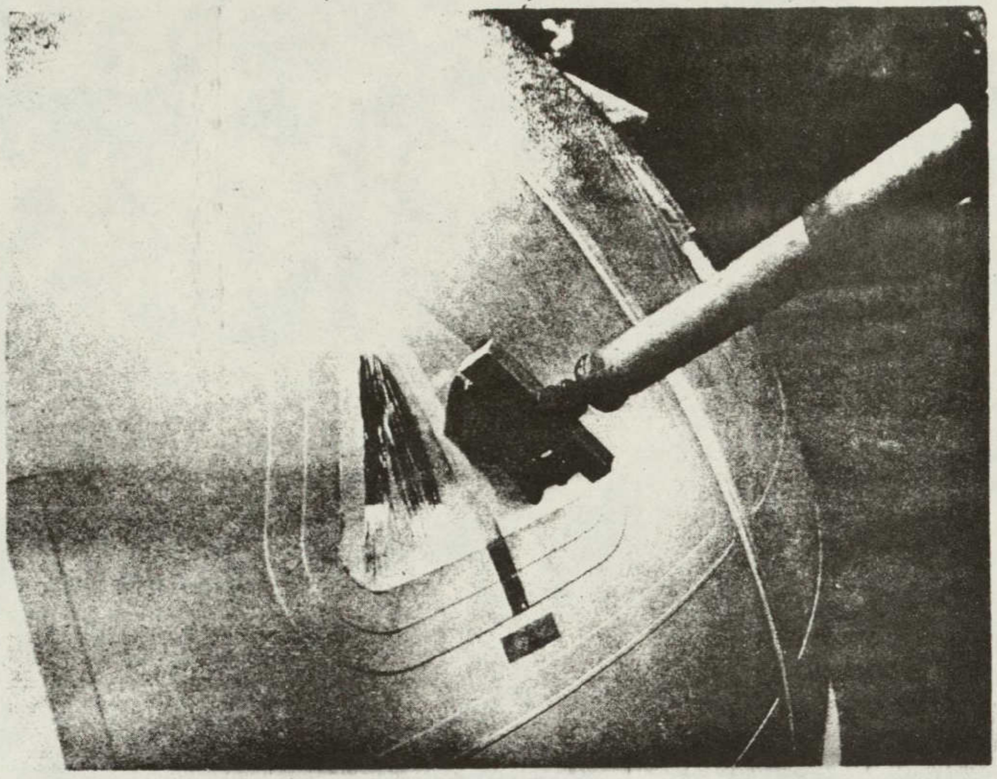


Figure 7-25. Tank support bracket prepared for weld operation.

Figure 7-26. Aft bulkhead with support brackets installed.

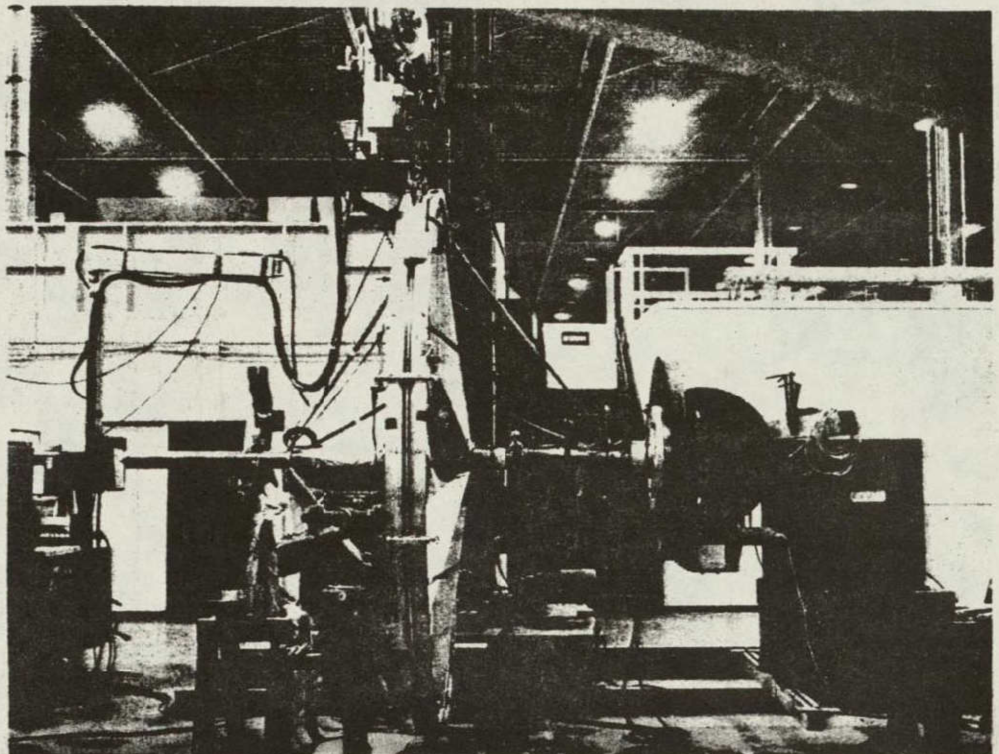


Figure 7-27. Girth weld tool setup.

Two temporary bulkhead supporting plugs were constructed to hold the bulkhead shape while sliding the bulkheads on and off the backup wheel. These lightweight stiff plugs were made from a laminated composite of styrofoam core and cardboard outer faces. The plugs will be set 30.48 cm (12 in.) back from the girth to be removed after welding by cutting the plugs into pieces which fit through the door opening. The plug in the forward bulkhead can be seen in Figure 7-28.

The final girth dimensions of the two bulkheads matched very close. The forward bulkhead measured 3.0304 cm (119.307 in.) in diameter and the aft bulkhead measured 3.0305 cm (119.310 in.) in diameter.

The bulkheads were assembled onto the girth weld fixture, as shown in Figure 7-29. The bulkhead expendable plugs served as guides over the fixture axle and controlled contour during the installation operation. The bulkheads were assembled on the girth weld ring for a fit check, then backed off for weld edge scraping. After this weld preparation, the two bulkheads were reinstalled on the girth wheel and the outer rings slid into position. The inner backup ring was expanded and the outer holddown rings were pressurized. The assembled system ready for welding is shown in Figure 7-30.

After welding, the internal tooling was disassembled and removed through the tank door as shown in Figure 7-31. The tank was then installed into the universal testing fixture as shown in Figure 7-32.

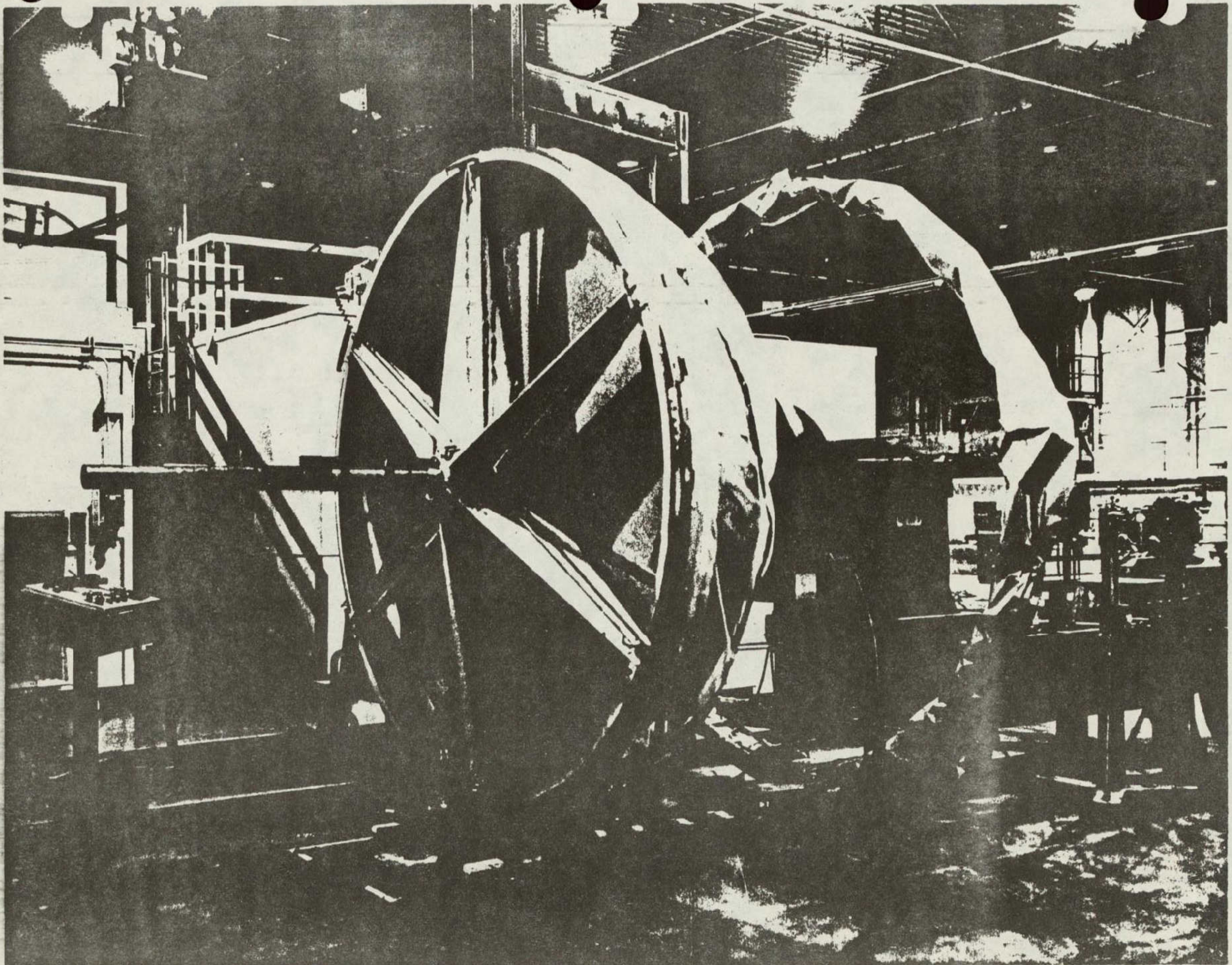


Figure 7-28. Girth weld fixture checkout. 15 9282

GENERAL DYNAMICS
Convair Division

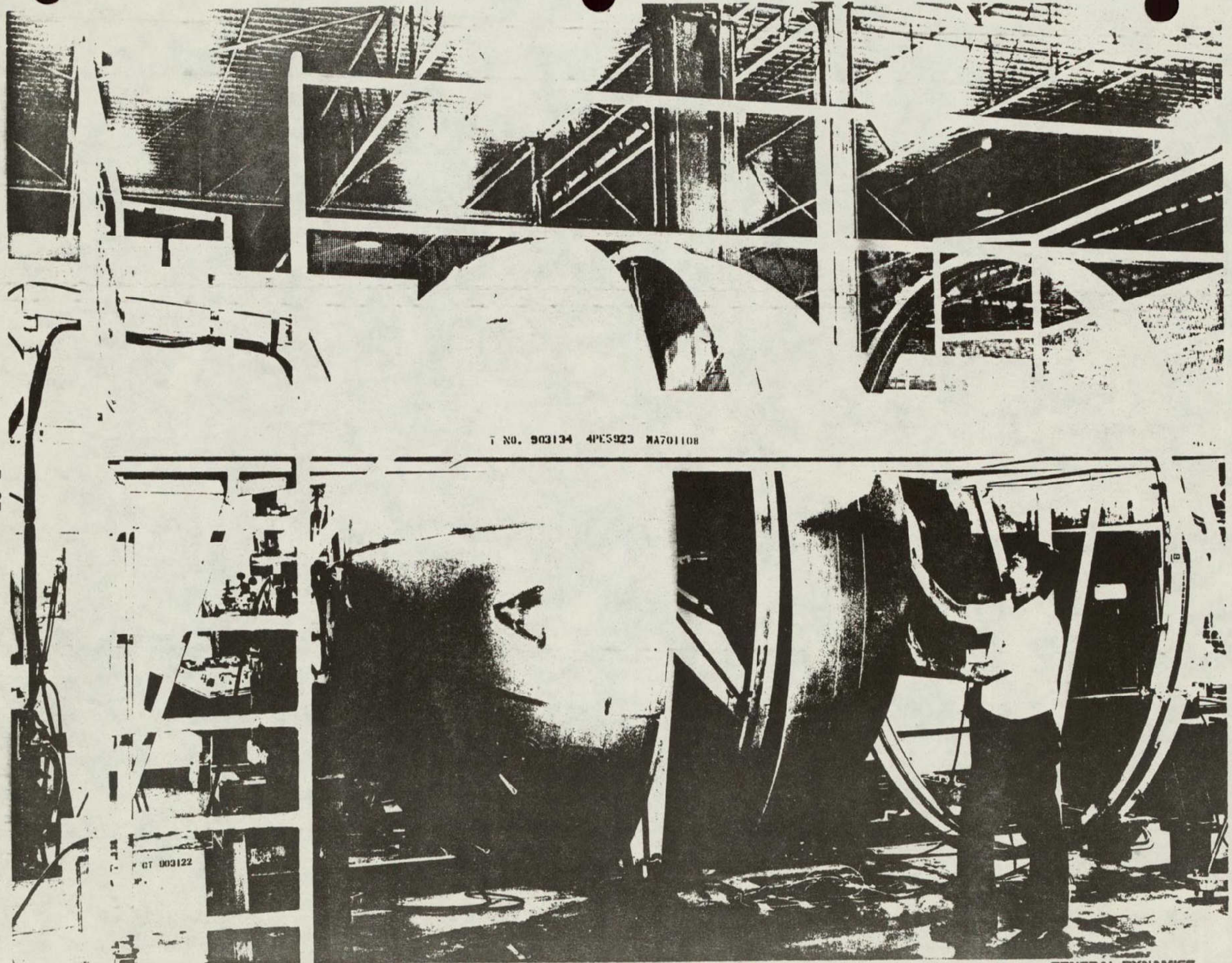


Figure 7-29. Bulkhead installation. 15 9463

GENERAL DYNAMICS
Convair Division

C-2

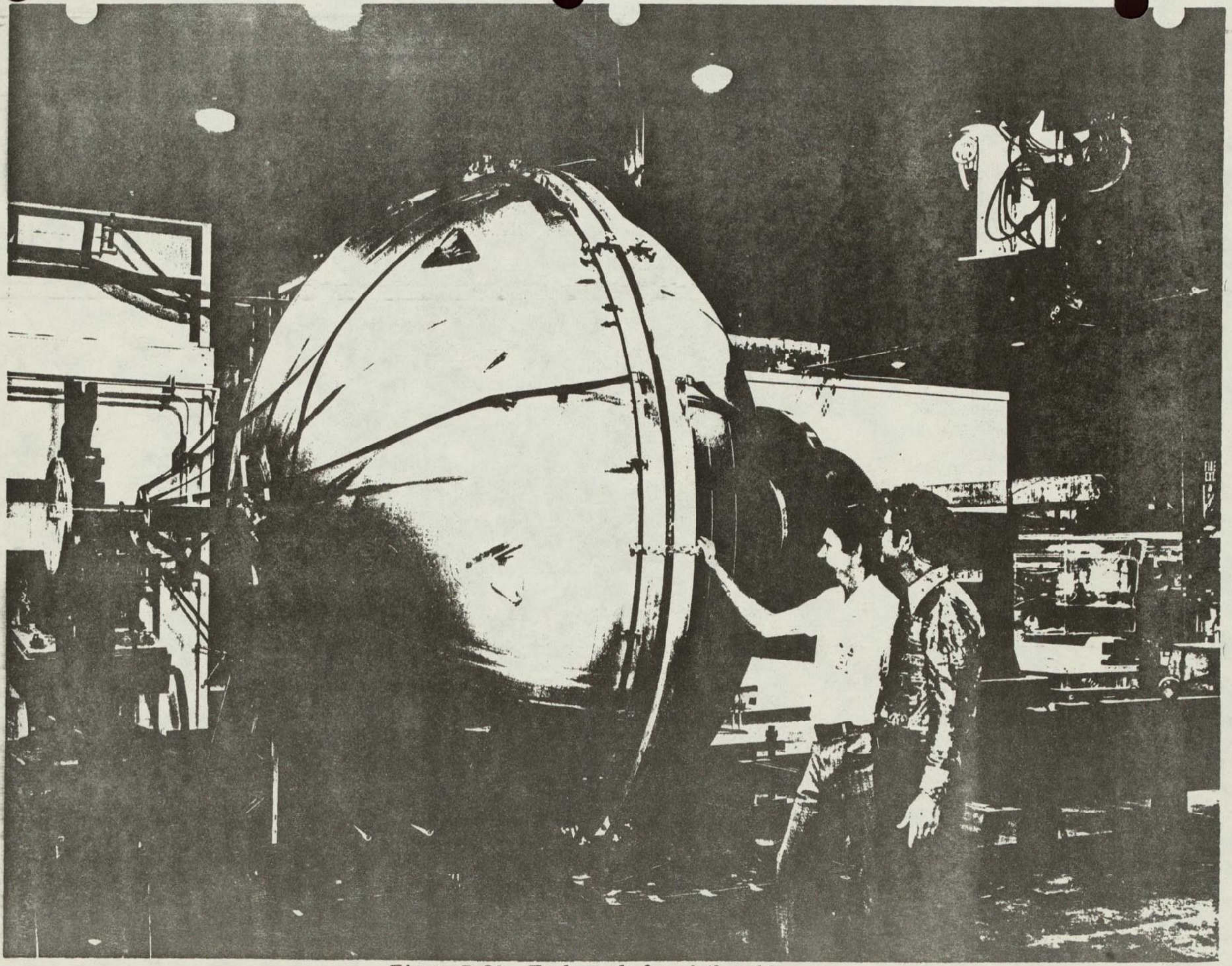


Figure 7-30. Tank ready for girth weld.

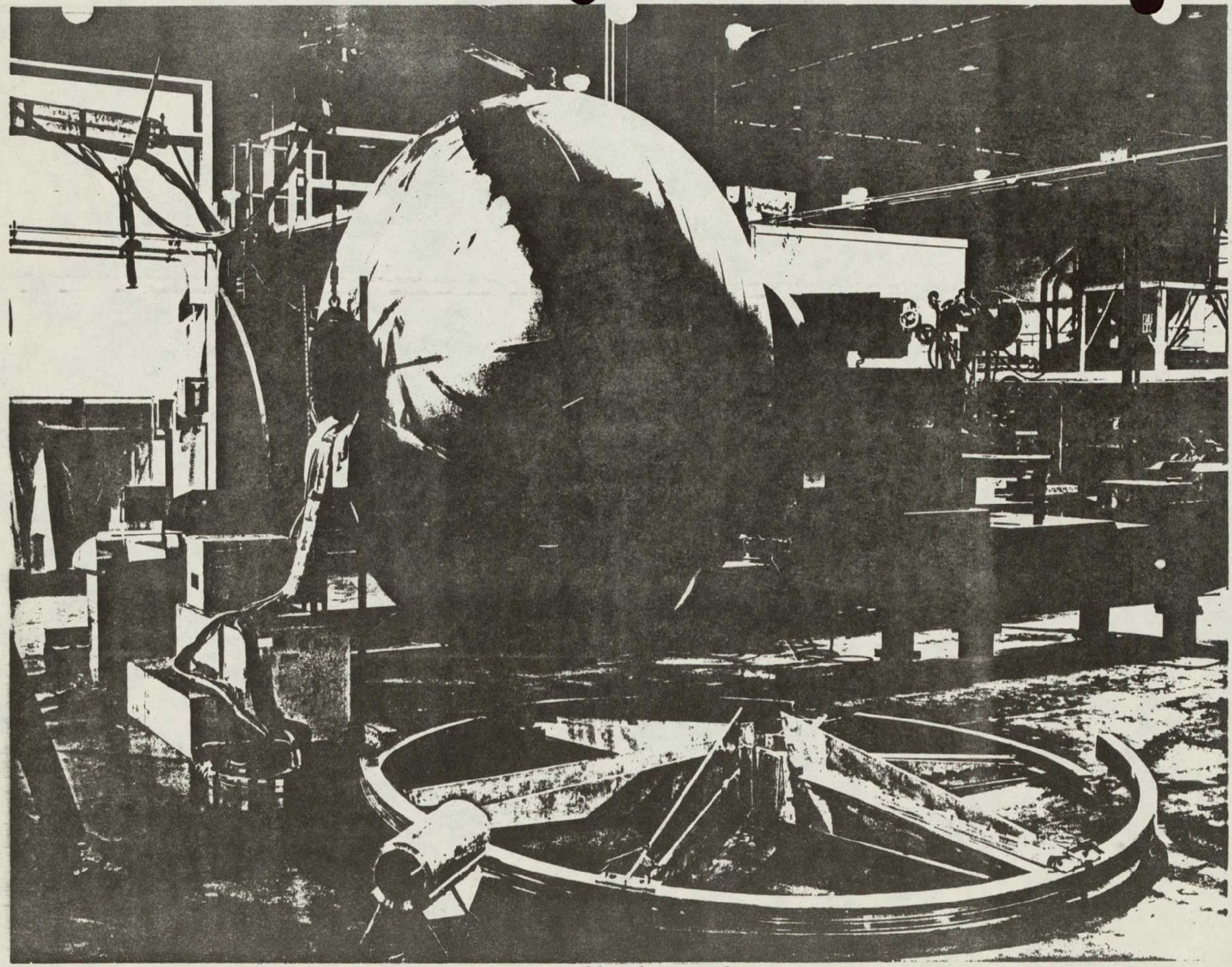


Figure 7-31. Weld tool removal.

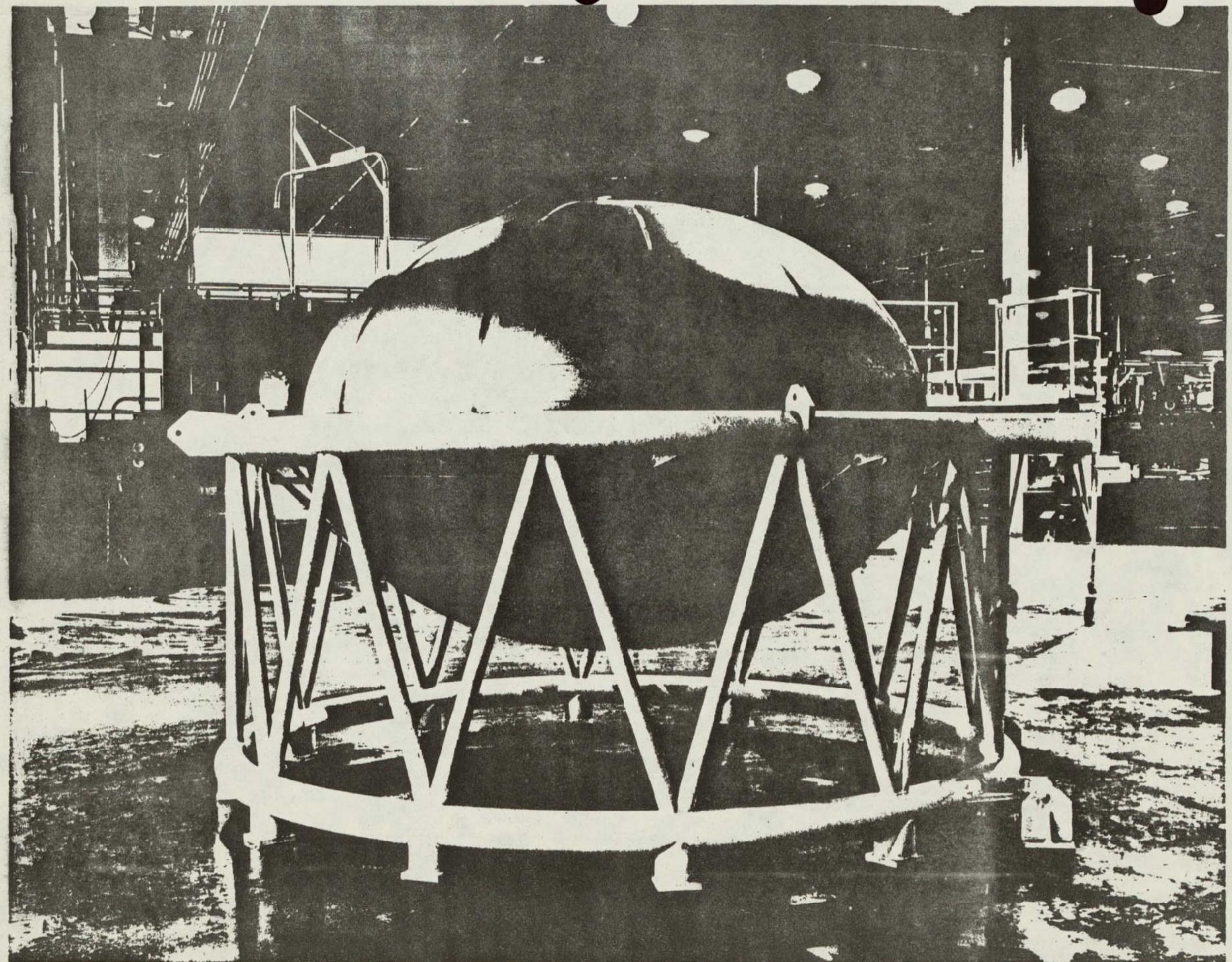


Figure 7-32. Completed tank. 15 10383

GENERAL DYNAMICS
Convair Division

8

CONCLUSIONS AND RECOMMENDATIONS

The designs developed in this study based on the full scale Tug requirements have been realistically optimized and could very well apply to the Orbital Transfer Vehicle (OTV). A similar study should be applied to the OTV requirements and follow similar study procedures while taking advantage of the analytical tools developed during this study. Unique requirements could dictate different optimum tank configurations.

The test tank was sized to be a structural representation of the predesign Tug LO_2 tank in contour and also gage by duplicating the membrane stress levels. Therefore, comparison of the weights per unit area can be used as an indication of the success of tank representation. The predesign tank weight as stated in Subsection 1.2 includes items like line supports and dump fittings which were not incorporated in the test tank. Therefore, for comparison purposes a representative unit area weight was developed which excluded those items. The comparative weights of 2.91 kg/m^2 for the predesign tank and 2.96 kg/m^2 for the test tank (actual weights) shows very good correllation and any test data derived from the test tank will be applicable to the full size tank.

The large scale test tank fabricated in this program should be tested as outlined in Appendix C to verify the tank original analysis and fabrication techniques. Additional testing as defined in Appendix D should also be accomplished to develop additional understanding of the relationship of fabricated systems versus laboratory test sample results.

APPENDIX A

DESIGN REQUIREMENTS

DOCUMENT

PD75-0044

CONTRACT NAS8-31370

LIGHTWEIGHT LO_2 AND LH_2 PROPELLANT TANKS

DESIGN REQUIREMENTS

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

1.0 INTRODUCTION

1.1 Objective

The objective of this report is to present minimum design criteria for the Space Tug main propellant tankage system. To meet this objective design requirements data applicable to the Space Tug main propellant tanks have been extracted from the references listed in Section 6.0 and compiled in this report as a single source document. These criteria are to be used as the basis for a study of Lightweight Designs and Materials for LO_2 and LH_2 Propellant Tanks for Space Vehicles (NASA MSFC Contract NAS8-31370).

1.2 Baseline Tug Description

The NASA MSFC baseline Space Tug configuration as detailed in Reference 2 was selected as the baseline vehicle for the lightweight propellant tank study.

The Space Tug is made up of a LH_2 tank, LO_2 tank and a RL-10 derivative IIB main engine with an extendable nozzle, and a body shell made up of a forward skirt, main skirt, and aft adapter (Figure 1.2-1). It has a hydraulic system for actuator control and an active thermal control system to regulate the heating load of the fuel cells. A helium bottle pressure system is included to provide for purging, valve control, and accumulator pressurization. The auxiliary propulsion system (APS)consisting of four thruster pods is provided for vehicle control and maneuvering. The Space Tug has a navigation guidance and control system, a rendezvous and docking system, a

measuring system and an electrical power and distribution system.

The vehicle is 9.1 meters (30 feet) long and 4.47 meters (176 inches) in diameter, including the 1.40 meter (55 inch) long main engine (retracted length). Usable propellants are 22,760 Kgm (50,177 pounds), unusable 274 Kgm (605 pounds).

The Tug (including Shuttle/Tug adapter) weight is 26,616 Kgm (58,679 pounds), the dry weight is 2,336 Kgm (5150 pounds), and the APS propellants are 130 Kgm (288 pounds). The weight summary is shown in Table 1.2-1.

The baseline 4,990 Kgm (11,000 lb) payload with c.g. 3.68 meters (145 inches) forward of the Tug/payload interface) established in the Space Tug Shuttle Interface Compatibility Study (Reference 8) will be used for evaluating Tug configurations and loads during the lightweight propellant tank study.

TABLE 1.2-1
BASELINE TUG WEIGHT SUMMARY

		Weight - Kgm (lb)
STRUCTURE		895 (1974)
Body Shell	415 (914)	
Fuel Tank & Supports	193 (425)	
Oxidizer Tank & Supports	110 (243)	
Thrust Structure	13 (29)	
Mounting Structure	45 (100)	
Payload & Umbilical Interface	119 (263)	
PROPULSION		610 (1346)
Engine	200 (442)	
Feed, Fill, Drain & Vent	116 (256)	
Pneumatic & Press	106 (234)	
Hydraulic	29 (63)	
Propellant Loading & Measuring	23 (50)	
APS	136 (301)	
THERMAL CONTROL		201 (441)
Active Thermal Control	32 (70)	
Fuel Tank Insulation	41 (90)	
Oxidizer Tank Insulation	18 (40)	
Insulation Purge	91 (200)	
Passive Thermal Control	19 (41)	
AVIONICS		418 (921)
Navigation Guidance and Control	70 (154)	
Data Management	72 (158)	
Communications	32 (72)	
Measuring System	42 (92)	
Electrical Power and Distribution	186 (410)	
Rendezvous & Docking	16 (35)	
10% GROWTH CONTINGENCY INCLUDING FASTENERS		212 (468)
TOTAL DRY WEIGHT		2336 (5150)

TABLE 1.2-1 (CONTINUED)

BASELINE TUG WEIGHT SUMMARY

UNUSABLE RESIDUALS		274 (605)
Trapped Propellant	68 (150)	
Trapped Gases	150 (330)	
Fuel Bias	29 (65)	
Hydraulic Fluid	2 (5)	
APS Reserve	13 (29)	
APS Trapped	9 (19)	
Trapped Water	3 (7)	
BURN OUT WEIGHT		2610 (5755)
EXPENDABLES		249 (547)
LOX Boiloff	60 (130)	
Fuel Boiloff	75 (165)	
Start/Stop	35 (77)	
Fuel Cell Reactants	79 (175)	
PROPELLANT RESERVES		136 (300)
USABLE PROPELLANTS		22760 (50177)
LH_2	3233 (7127)	
LOX	19396 (42762)	
APS	131 (288)	
FIRST IGNITION WEIGHT		25755 (56779)
ORBITER INTERFACE ACCOMMODATIONS AND BOTTLES (includes contingency)		862 (1900)
Adapter Structure	307 (676)	
Propulsion	81 (178)	
Dump Press	57 (126)	
Avionics	213 (470)	
JSC Fittings	204 (450)	
GROUND LIFT-OFF		26617 (58,679)

Tug geosynchronous payload sensitivities to changes in structure weight are:

$$\frac{\Delta \text{ Payload}}{\Delta \text{ Structure Wt}} = -2.62 \text{ (Deploy mission)}$$

$$\frac{\Delta \text{Payload}}{\Delta \text{Structure Wt}} = -1.38 \text{ (Retrieve mission)}$$

During the lightweight tank study these payload sensitivities will be used to assess the performance impact of Tug tank and structure weight changes.

1.3 LH_2 Tank Description

The baseline Space Tug LH_2 tank is a suspended monocoque shell 443.2 cm (174.5 inches) long with a 429.3 cm^2 (169.0 inch) inside diameter constructed of 2219-T87 aluminum alloy. The tank uses elliptical bulkheads ($a/b = \sqrt{2}$) and has a total internal volume of 49.5 cubic meters (1748 cubic feet).

The baseline LH_2 tank supports consist of 16 fiberglass struts (8 pairs) and eight lateral roller supports forward. The apex of each aft strut pair is located on the tank. The aft bulkhead is reinforced to distribute local loads from the strut pair apexes to the membrane. Discrete reinforcing pads are provided on the tank cylinder for the forward roller attachments.

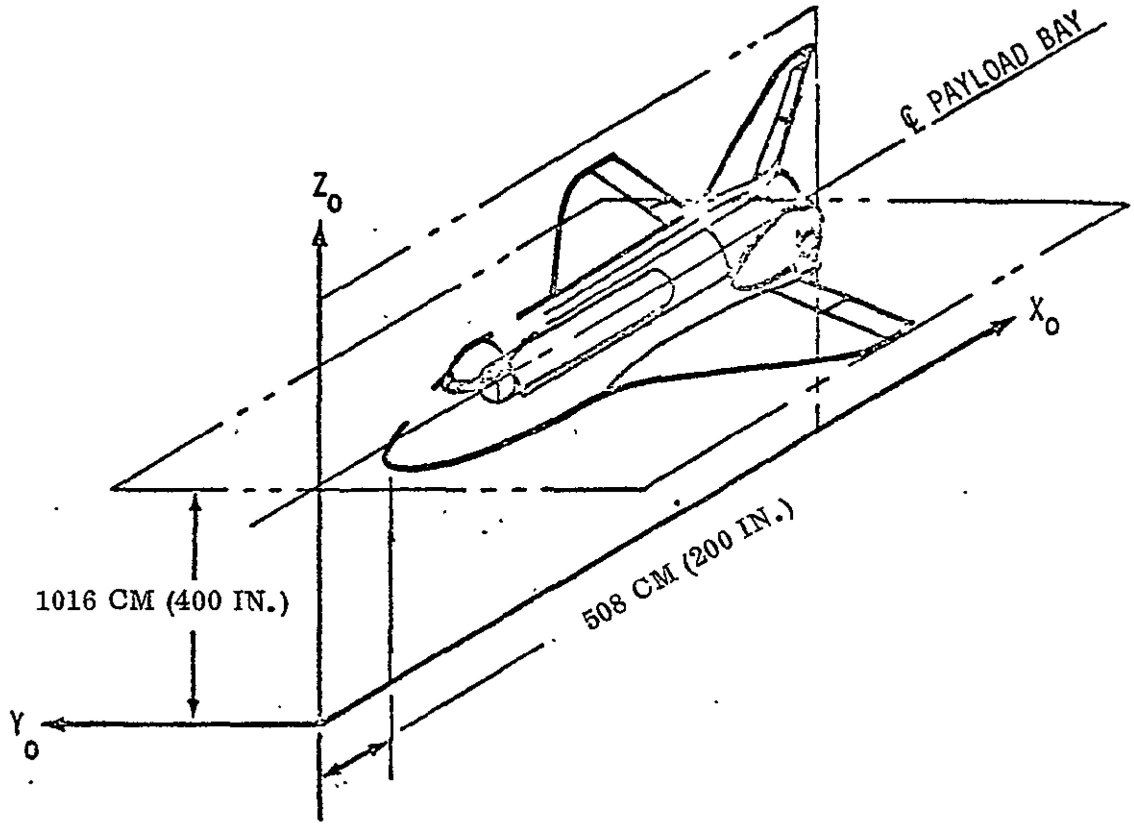
1.4 LO_2 Tank Description

The LO_2 tank is a 365.8 cm (144.0 inch) diameter by 258.6 cm (101.8 inch) high ellipsoid constructed of 2219-T87 aluminum alloy. The tank has a capacity of 18.1 cubic meters (640 cubic feet). The baseline LO_2 tank supports consist of 32 fiberglass struts (16 pairs) attached to the aft bulkhead. The aft bulkhead is reinforced to distribute local loads from the strut pair apexes to the membrane. The

thrust structure for the RL-10 main engine is attached directly to the LO_2 tank by eight struts. All engine thrust loads are reacted directly into the LO_2 tank.

1.5 Reference Coordinate System

The Orbiter coordinate system from Reference 4 is shown in Figure 1.5-1. This coordinate system is used for the Space Tug and will also be the reference coordinate system for the lightweight space vehicle propellant tank study.



TYPE: ROTATING, ORBITER REFERENCED

ORIGIN: APPROXIMATELY 200 INCHES AHEAD OF THE NOSE AND APPROXIMATELY 400 INCHES BELOW THE CENTERLINE OF THE PAYLOAD BAY

ORIENTATION AND LABELING:

THE X AXIS IS PARALLEL TO THE CENTERLINE OF THE PAYLOAD BAY, NEGATIVE IN THE DIRECTION OF LAUNCH

THE Z AXIS IS POSITIVE UPWARD IN LANDING ATTITUDE

THE Y COMPLETES THE RIGHT-HANDED SYSTEM

THE STANDARD SUBSCRIPT IS 0

FIGURE 1.5-1 REFERENCE COORDINATE SYSTEM

2.0 CONFIGURATION REQUIREMENTS

To provide as much flexibility as possible in optimizing propellant tank configurations during the lightweight propellant tank study, firm geometric constraints will be limited to required propellant volume and available envelope within the Orbiter cargo bay for the Space Tug. All other configuration requirements may be varied to best meet the overall Tug systems objectives.

2.1 LH_2 Tank

2.1.1 Envelope

The LH_2 tank maximum inner diameter shall be 429.3 cm (169.0 in.) (Ref 2). It shall be a design goal to minimize overall tank length. However, tank length is not fixed and may be varied as a function of bulkhead geometry to meet the diameter and volume requirements.

2.1.2 Volume

The Tug LH_2 tank volume (unpressurized) at room temperature shall be 49.5 m^3 (1748 ft^3) (Ref 2).

2.1.3 Access

A single access opening shall be provided at the apex of the LH_2 tank forward bulkhead. The access opening shall be of minimum diameter consistent with the requirements for removal and replacement of internal components, installation of work platforms and other support equipment, and personnel access.

2.1.4 Support Provisions

The LH_2 tank shall be suspended within the 447 cm (176 inch) diameter Space Tug structural shell by means of load carrying thermal isolation struts, in pairs, at the aft end of the tank. The apex of each strut pair shall be located on the tank. A lateral support system shall be provided at the forward end of the tank. The number, location and type of supports shall be selected to optimize structural and thermal performance of the system.

2.2 LO_2 Tank

2.2.1 Envelope

The LO_2 tank maximum inner diameter shall be 429.3 cm (169.0 inches) (expected maximum diameter is 365.8 cm (144.0 inches). It shall be a design goal to minimize overall tank length. However, tank length is not fixed and will vary as a function of bulkhead geometry to meet the volume requirement.

2.2.2 Volume

The Tug LO_2 tank volume (unpressurized) at room temperature shall be 18.1 m^3 (640 ft^3).

2.2.3 Access

A single access opening shall be provided at the apex of the LO_2 tank aft bulkhead. The access opening shall be of minimum diameter

consistent with the requirements for removal and replacement of internal components, installation of work platforms and other support equipment, and personnel access.

2.2.4 Support Provisions

The LO_2 tank shall be suspended within the 447 cm (176 inch) diameter Space Tug structural shell by means of load carrying thermal isolation struts, in pairs. The apex of each strut pair shall be located on the tank. The number, location and type of supports shall be selected to optimize structural and thermal performance of the system.

3.0 FUNCTIONAL REQUIREMENTS

In addition to their primary function of propellant storage, the following functional requirements must be met by the Space Tug LH_2 and LO_2 tanks.

3.1 Operational Requirements

3.1.1 Missions

The baseline Tug shall be capable of delivering to geosynchronous orbit 2722-3175 Kgms (6000-7000 lbs) of payload (spacecraft-SC) or retrieving from geosynchronous orbit 1360-2268 Kgms (3000-5000 lbs) of spacecraft. Within this performance, the Tug shall be capable of, on a single mission,

(1) deploying up to three SC into geosynchronous orbit, assuming two at the same longitude, and retrieve one, or

(2) deploying one SC into low earth orbit and retrieving one, or

(3) deploying one SC into planetary trajectory.

The baseline Tug shall be capable of the following mission durations:

Liftoff through deployment	2 to 16 hours
From deployment to retrieval	up to 154 hours
Retrieval through landing	12 to 28 hours

Typical Shuttle missions can be divided into three phases: Boost, on orbit, and entry and landing. During the boost and on-orbit phases the LH_2 and LO_2 tanks shall be assumed full of propellants (or off-loaded as required to meet the 29480 kgm (65000 lb) Orbiter payload capability).

During the entry and landing phase the LH_2 and LO_2 tank shall be assumed empty of all propellants except 247 Kgm (545 lb.) of residuals.

3.1.2 Mission Abort

The Space Shuttle has a requirement of intact abort. There are four abort modes depending on the time in the mission when abort occurs. These abort modes are shown in Table 3.1-1. Reference 10 specifies inflight dumping of both Tug propellants for abort operations. During the entry and landing mission phases after a mission abort the LH_2 and LO_2 tanks shall be assumed empty of all propellants.

The Tug propellant tanks shall be compatible with all shuttle abort modes and procedures specified in Reference 4.

Table 3.1-1 Shuttle Abort Modes

ABORT MODE	MODE LIMITS TIME FROM LAUNCH (SEC)	MIN SSME BURN TIME (SEC)	MIN OMS BURN TIME (SEC)	0-g TIME (SEC)
RETURN TO LAUNCH SITE (RTLS)	125-240	325	–	–
ABORT ONCE AROUND (AOA)	220-400	105	100	3720
ABORT TO ORBIT (ATO)	247-306	235	240	15000
ABORT FROM ORBIT (AFO)	–	–	120	24000

3.1.3 Fluid Transfer

The Tug propellant tanks shall be capable of being loaded or off-loaded with propellants and pressurants while the Tug is in the Shuttle cargo bay on the launch pad in the vertical position. The Tug propellant tanks shall be capable of safely dumping propellants while the Tug is in the Shuttle cargo bay during boost and on-orbit operations.

The Tug propellant tanks shall be capable of safely venting propellants while on the pad, during Shuttle operations, and during Tug operations.

3.1.4 Leakage

It shall be a design goal to minimize leakage sources of the Tug propellant tanks and equipment by use of all welded or brazed construction where practical. A fracture mechanics analysis shall be performed on each propellant tank to demonstrate no leakage due to crack growth through the thickness of the tank during the Tug design life. Each tank shall be enclosed in a separate leakage containment membrane which shall be vented outside the Orbiter. The leakage containment system shall contain provisions for propellant leak detection. For access doors, pass throughs, piping flanges, etc., which require removal from the propellant tanks, seals shall be provided which minimize propellant leakage.

3.2 Reusability and Service Life

The baseline Space Tug shall be retrievable and refurbishable. The Tug propellant tanks shall be designed for a service life of 50 missions. It shall be a design goal to minimize maintenance and refurbishment for the service life of the tanks.

3.3 Subsystem Interfaces

The following subsystems interface with the Tug LH_2 and LO_2 tanks:

1. Propellant feed and fill/drain
2. Pressurization and vent
3. Propellant loading and monitoring
4. Tank Support
5. Thermal Control

In addition the LO_2 tank interfaces directly with the main propulsion subsystem.

Requirements for Component mounting on the propellant tanks for each of these subsystems are listed in Tables 3.3-1 and 3.3-2 for the LH_2 and LO_2 tanks respectively.

Required propellant tank penetrations to accommodate subsystems provisions are tabulated in Table 3.3-3.

Detailed subsystem interface requirements for the LH_2 and LO_2 tanks are discussed in the following subsections.

3.3.1 Propellant Feed, Fill and Drain

The Tug propellant feed, fill and drain system is shown schematically in Figure 3.3-1. The LH_2 feedline inlet has a "Siphon" type suction line rather than the sump type of inlet used for the LO_2 tank. Submerged valving on the LH_2 side were selected to reduce heat leaks and propellant leakage. The valves are pneumatically opened, normally-closed, shutoff valves. Prevalves are located in both the LH_2 and LO_2 feedlines to isolate the propellant tanks from the engine.

Table 3.3-1. Tug LH_2 Tank Subsystem Mounting Requirements

Subsystem	Component	Location	No. Req'd	Description	Function
Propellant Feed and Fill & Drain	Fill & Drain Valve	Internal-Aft Bhd	2	2 separate parallel 12.7 cm (5 in.) valves for redundancy.	Provide LH_2 fill, drain & dump.
	Main Engine Propellant Feed Valve	External-Aft Bhd	1	Single 8.9 cm (3.5 in.) valve.	Supply LH_2 to main engine
	Fuel Cell Supply Valve	External Aft Bhd	1	Single in Valve	Supply LH_2 to fuel cell.
	Anti-vortex baffle	Internal Aft Bhd	1	Baffle at main engine propellant feed outlet	Prevent propellant pull-through at low propellant levels.
	Propellant Slosh Baffles	Internal Side Wall	TBD		Reduce propellant slosh during operations with partially filled tanks.
Pressurization and Vent	Vent Valve	Internal Fwd Bhd	2	2 separate 7.6 cm (3 in.) valves for redundancy	Provide LH_2 tank ground and flight venting (non-zero g operation)
	Zero g Vent System	Internal Fwd Bhd	1	Thermodynamic Vent System	Provide venting during zero g operation
Propellant Loading & Monitoring	Liquid Level Sensor	Internal	1	Capacitive mass probe extending full tank length.	Provide propellant level sensing and monitoring
Tank Support	Tank Support Struts	External Fwd & Aft Bhd	12 aft 6 Fwd	Individual struts in pairs on aft bhd. individual supports on fwd bhd for lateral support.	Support tank within Tug shell.
Thermal Control	Insulation & purge/leakage containment membrane.	External Entire Tank Surface		Super insulation and flexible purge/leakage containment membrane.	Provide thermal control - minimize propellant boiloff.

Table 3.3-2. Tug LO_2 Tank Subsystem Mounting Requirements

Subsystem	Component	Location	No. Req'd	Description	Function
Propellant Feed and Fill and Drain	Fill and Drain Valve	External Aft Bhd	2	2 separate parallel 12.7cm (5 in) valves for redundancy.	Provide LH_2 fill, drain and dump.
	Main Engine Propellant Feed Valve	External Aft Bhd	1	Single 8.9 cm (3.5 in) valve.	Supply LO_2 to main engine.
	Fuel Cell Supply Valve	External Aft Bhd	1	Single Valve	Supply LO_2 to fuel cell.
	Anti-vortex baffle	Internal Aft Bhd	1	Baffle at main engine propellant feed outlet.	Prevent propellant pull through at low propellant levels.
	Propellant slosh baffles	Internal side wall	TBD		Reduce propellant slosh during operations with partially filled tank.
	LO_2 Topping Valve	External Aft Bhd	1	Single 1.91 cm (0.75 in) valve.	Provide LO_2 topping
Pressurization and Vent	Vent Valve	External Aft Bhd	2	2 separate parallel 5.1 cm (2 in) valves for redundancy.	Provide ground and flight venting (non-zero g operation).
	Zero g vent system	Internal Fwd Bhd	1	Thermodynamic vent system	Provide venting during zero g operation.
Propellant Loading and Monitoring	Liquid Level Sensor	Internal	1	Capacitive mass probe extending full tank length.	Provide propellant level sensing and monitoring.

Table 3.3-2. Tug LO_2 Tank Subsystem Mounting Requirements (Continued)

Subsystem	Component	Location	No. Req'd	Description	Function
Main Propulsion	Main propulsion engine	External Aft Bhd	1	RL-10 Cat IIB engine	Provide main propulsion for Tug
Tank Support	Tank Support Struts	External Aft Bhd	24	Individual struts in pairs on aft bhd.	Support tank within Tug shell.
Thermal Control	Insulation & purge/ leakage containment membrane.	External Entire Tank Surface	--	Super insulation and flexible purge/leakage containment membrane.	Provide thermal control minimize propellant boiloff

Table 3.3-3

Tug Propellant Tank Penetrations

System	Interface	LH_2 Tank Dia. cm (in.)	LH_2 Tank No. Req'd	LO_2 Tank Dia. cm (in.)	LO_2 Tank No. Req'd
Propellant Feed Fill & Drain	Fill & Drain	12.7 (5.0)	1	12.7 (5.0)	1
	Main Propulsion Feed	8.9 (3.5)	1	8.9 (3.5)	1
	LO_2 Topping	-	0	1.91 (0.75)	1
	Fuel Cell	TBD	1	TBD	1
	He Pressurization (Fill & Drain Valve Operation)	0.64 (0.25)	3	-	0
Pressurization and Venting	Tank Pressurization	1.27 (0.50)	1	1.27 (0.50)	1
	Normal Vent	7.6 (3.0)	1	5.1 (2.0)	1
	He Pressurization (Vent Valve Operation)	0.64 (0.25)	2	-	0
	Zero g vent	TBD	1	TBD	1
	Zero g vent (electrical)	TBD	1	TBD	1
Propellant Loading & Monitoring	Liquid Level Sensing & Monitoring (Electrical)	TBD	1	TBD	1

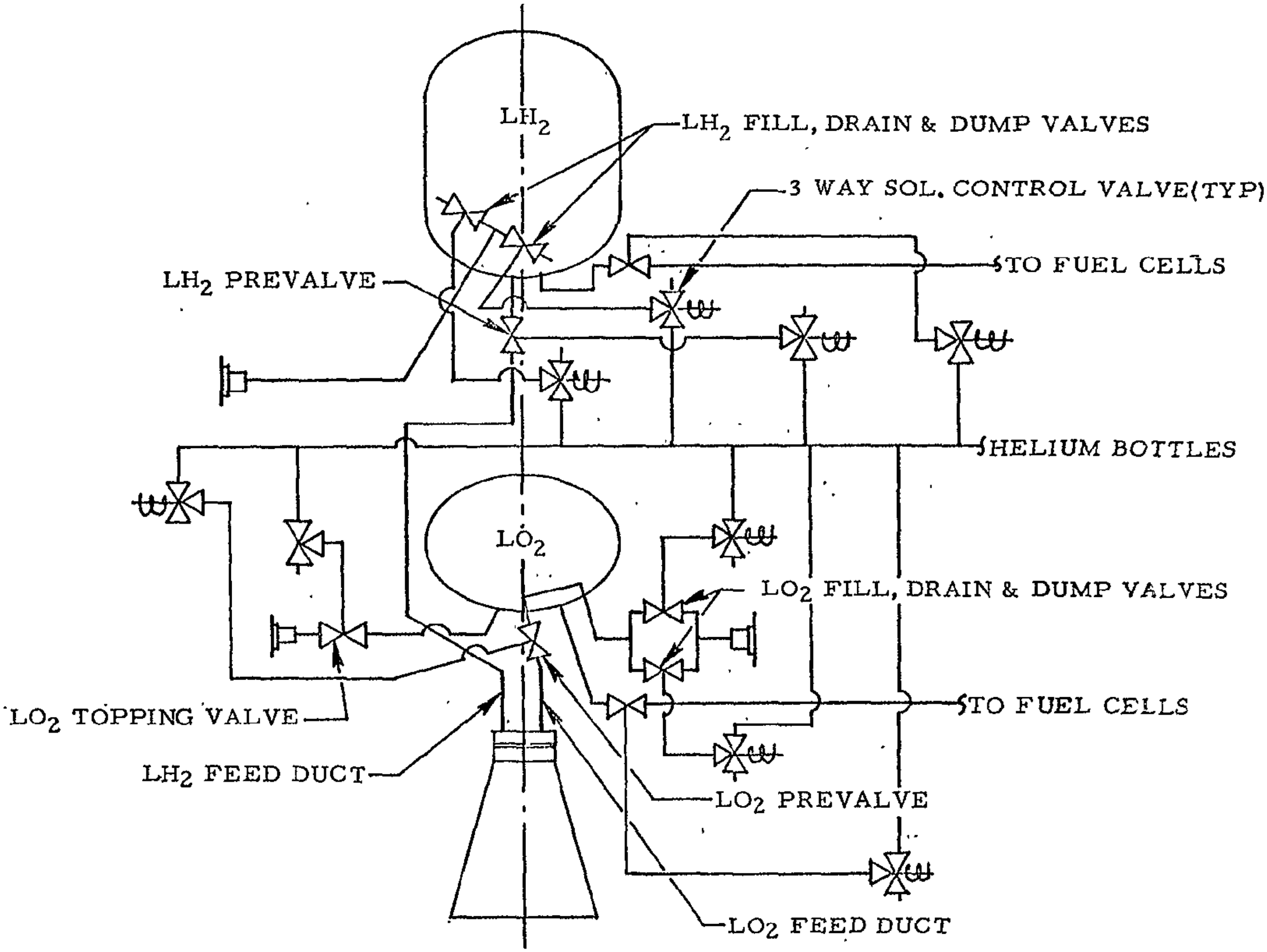


Figure 3. 3-1 PROPELLANT FEED, FILL & DRAIN SYSTEM

Both the LH_2 and LO_2 fill systems contain dual fill and drain valves to provide redundancy for the critical dump operation during a launch abort.

The LH_2 and LO_2 feed systems are both nominal 8.9 cm (3.5 in) diameter systems. The LH_2 & LO_2 fill and drain systems are both nominal 12.7 cm (5.0 in) diameter systems. The LO_2 topping system is a nominal 1.91 cm (0.75 in) diameter system.

Pneumatic supply (Helium) is required to operate the Tug propellant tank fill and drain valves. The Helium supply for valve operation uses a nominal 0.64 cm (0.25 in) diameter system. A total of three Helium supply lines are required for operation of the fill and drain valves in the LH_2 tank. Two lines are required for operation of the external fill and drain valves on the LO_2 tank.

The Tug LH_2 and LO_2 tanks shall be designed to provide the required mounting provisions for the propellant feed and fill and drain system components listed in Tables 3.3-1 and 3.3-2. In addition, the tanks shall provide the propellant feed and fill and drain system penetrations shown in Table 3.3-3.

3.3.2 Pressurization and Vent

The Tug main propellant tank pressurization system is shown schematically in Figure 3.3-2. An ambient helium pressurization system is provided for LH_2 and LO_2 prepressurization. LH_2 and

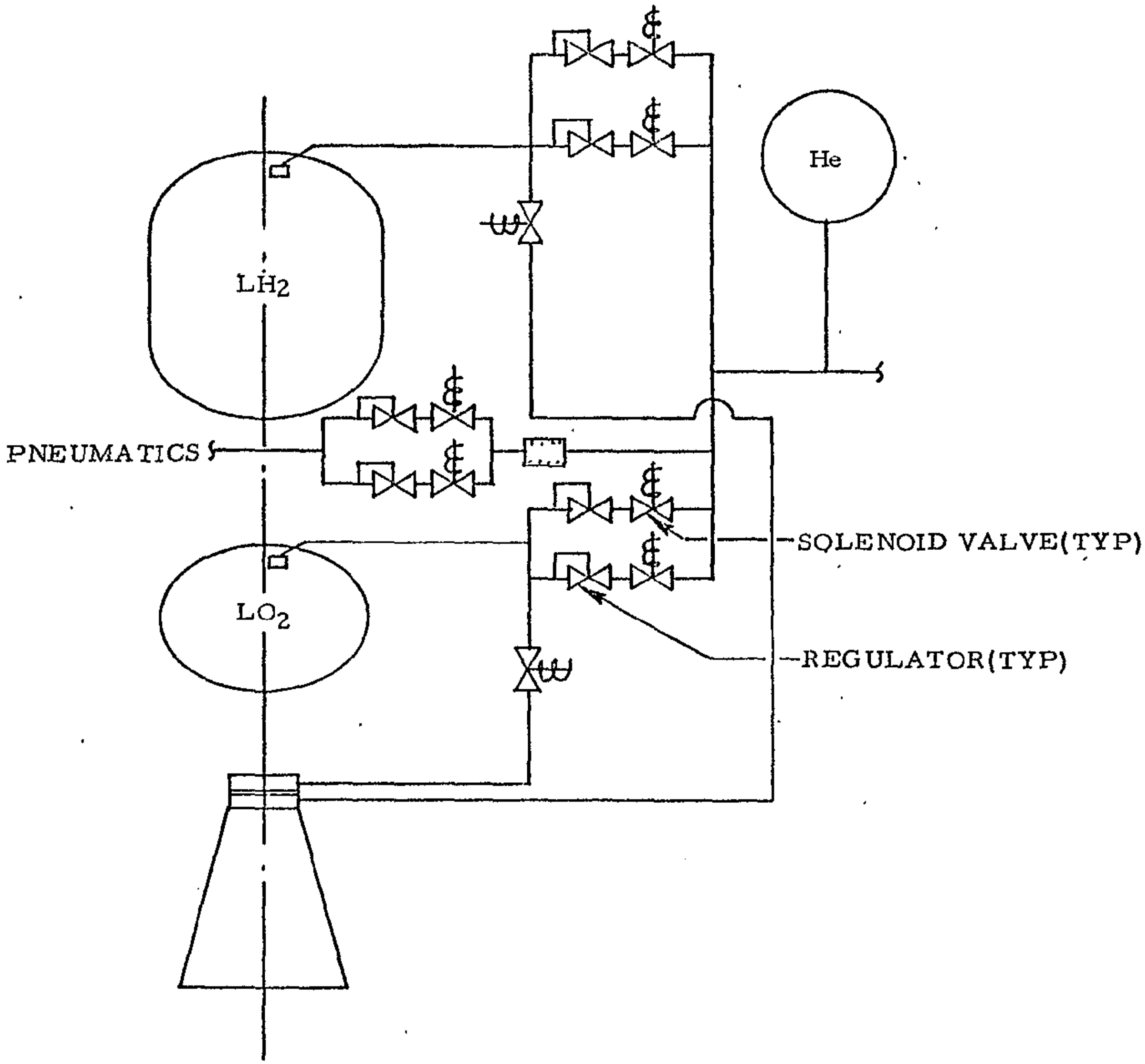


Figure 3.3-2 PRESSURIZATION SYSTEM

LO_2 main stage pressurization is provided from GH_2 and GO_2 tap-offs on the main engine.

Redundancy in the regulation of pressurization is provided by two regulators in parallel with a shutoff valve in each leg.

Nominal 1.27 cm (0.50 in) diameter systems are used for both LH_2 and LO_2 tank pressurization.

The propellant vent and relief system configuration is shown schematically in Figure 3.3-3. Both the LH_2 and LO_2 tank vent and relief systems are composed of two subsystems. The primary vent systems are functional during the loading, ascent, and positive acceleration periods of Tug operation.

The LH_2 vent system is contained entirely within the tank while the LO_2 vent system is external to the tank.

The secondary vent system is required to vent the LH_2 and LO_2 tanks during periods of zero or low acceleration when propellants are not settled. A zero gravity thermodynamic vent system is used in both tanks. The thermodynamic vent requires electrical power for mixing to operate and vents only gas even though both gas and liquid may be present.

Redundancy is provided through the use of dual valving. The primary LH_2 and LO_2 vent systems are nominal 3 inch diameters and the secondary systems are TBD inch in diameter.

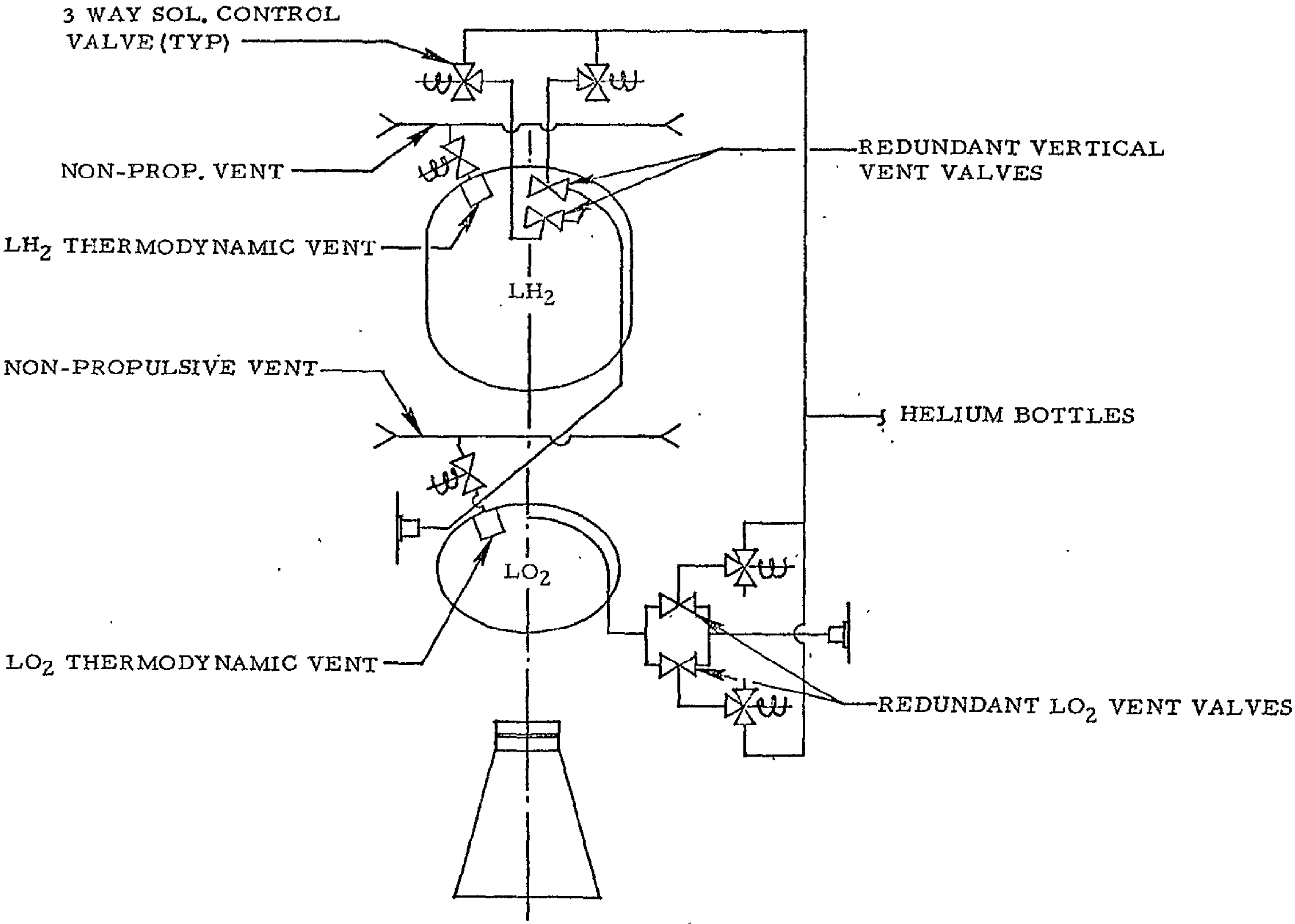


Figure 3.3-3 VENT/RELIEF SYSTEM

Pneumatic supply (Helium) is required to operate the LH_2 and LO_2 primary vent valves. The helium supply for valve operation uses a nominal 0.64 cm (0.25 in) diameter system. Two helium supply lines are required for vent valve operation for each tank.

The Tug LH_2 and LO_2 tanks shall be designed to provide the required mounting provisions for pressurization and vent system components listed in Tables 3.3-1 and 3.3-2. In addition, the tanks shall provide the pressurization and vent system tank penetrations shown in Table 3.3-3.

3.3.3 Propellant Loading and Monitoring

The propellant loading and monitoring system consists of capacitive mass probes located in each propellant tank together with an electronic assembly and power supply, point level sensors for sensing overfill and low level conditions and associated brackets and wiring.

The Tug LH_2 and LO_2 tanks shall be designed to provide the required mounting provisions for propellant loading and monitoring components listed in Tables 3.3-1 and 3.3-2. In addition, the tanks shall provide the propellant loading and monitoring system tank penetrations shown in Table 3.3-3.

3.3.4 Tank Support

The Tug LH_2 and LO_2 tanks shall incorporate interface provisions for the tank support subsystems described in Sections 2.1.4 and 2.2.4.

3.3.5 Thermal Control

The Tug LH_2 and LO_2 tanks shall incorporate interface provisions for the thermal control subsystem described in Section 3.4.

3.3.6 Main Propulsion

The Tug main propulsion system which consists of a 92250 N (15000 lb) thrust Pratt and Whitney RL10 Cat IIB engine with extendable nozzle and its control subsystem is mounted on the aft bulkhead of the LO_2 tank. The LO_2 tanks aft bulkhead shall incorporate support provisions for the Tug main propulsion system components listed in Table 3.3-2.

3.4 Thermal Control

The Tug propellant tanks shall be insulated to minimize heat leaks and resulting propellant boiloff.

Insulation consists of a 1.96 cm (0.77 in) thick 23 layer blanket of goldized Kapton sheets, a leakage membrane made from a single aluminized Kapton layer reinforced with Dacron cloth and an outer purge bag made from Teflon impregnated Dacron cloth as shown in Figure 3.4-1.

The insulation is purged with helium prior to launch to remove contaminants and is pressurized with helium during reentry to prevent absorption of atmospheric contaminants.

Additional thermal isolation of the tanks is provided by the tank support struts which are made of low thermal conductivity material.

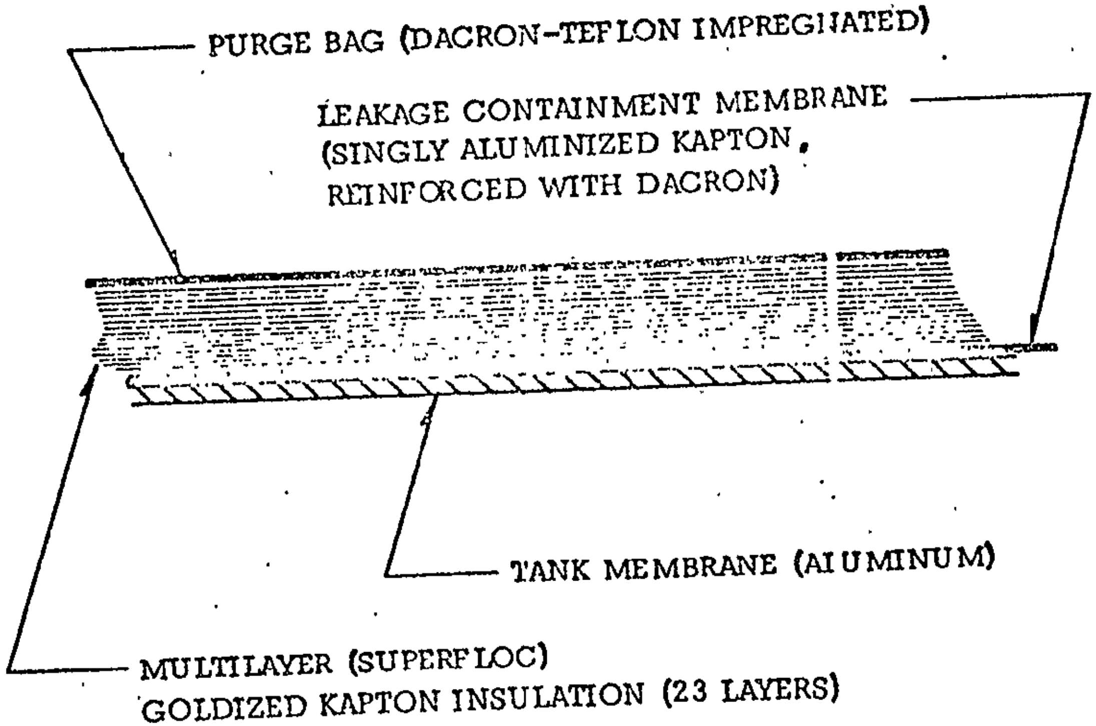


Figure 3.4-1 Thermal Protection

3.5 Safety and Reliability

The Tug propellant tanks shall meet all the safety and reliability requirements of Ref. 1. Specific Tug propellant tank related safety and reliability requirements which must be satisfied in the tank design effort of the lightweight propellant tank study are listed below. The propellant tank safety requirements are presented in the following format:

a. General Safety Requirements

b. Operational Safety Requirements

c. System Safety Requirements

3.5.1 General Safety Requirements

a. No single Tug failure shall result in a hazard which jeopardizes the flight or ground crews of the Shuttle, general public, public/private property and the ecology.

b. Materials, fluids, etc., shall not be released or ejected into the payload bay from the Tug. Venting, relief, and release of material from the Tug shall be through the Orbiter provided vent system. Control of the venting, etc., by the Orbiter for certain mission phases may be required.

c. Appropriate safety factors shall be used where necessary to minimize the possibility of failures which might affect manned safety (i.e., structures, pressure vessels, etc.) and shall be maintained under abort load conditions.

d. Tug propellants and pressurants shall be reduced to a predetermined safe level prior to Tug retrieval.

e. Tug operations and energy levels shall be held to a minimum while aboard or in the near vicinity of the Orbiter.

f. Tug must not generate forces, impulses or momentum changes which will produce adverse effects beyond Orbiter GN&C capability while aboard the Orbiter (i.e., fluid sloshing in partly filled tanks, etc.).

g. Main propellant dump capability shall be available from propellant servicing throughout the mission, including abort

h. Provisions shall be made for detecting the presence of spilled hazardous fluids or materials during handling or transfer.

i. All subsystems except primary structure and pressure vessels shall be designed to fail safe in the vicinity of the Shuttle Orbiter. Primary structure and pressure vessels shall be designed to safe-life criteria.

j. All safety subsystems shall be designed to fail operational in the vicinity of the Shuttle Orbiter.

3.5.2 Operational Safety Requirements

a. Tank pressures shall be vented and verified before opening a tank access cover.

b. Propellant tank venting will be controlled through the Orbiter overboard venting system to prevent accumulation of toxic or explosive vapors in the Orbiter payload bay.

c. Purge provisions shall be available to neutralize propellant leaks during and after propellant servicing and after Orbiter landing.

d. Transportation and hoisting load limits, static and dynamic, shall be TBD less than flight load limits in all cases.

e. The pressures, temperatures and other parameters which indicate the status of hazardous fluids or materials shall be verified before the Tug is transported.

f. Tug pressurized systems shall have a maximum operating pressure helium leak check before installation into the Orbiter payload bay and an inert gas leak check before loading propellants.

g. Propellant tank pressures where practical shall not be increased to operational values until TBD distance from the Orbiter after deployment.

h. Tug propellant tank integrity shall be verified, pressures and hazardous fluid quantities shall be reduced to a safe value, and ordnance circuits shall be safed before Tug retrieval operations begin.

i. Provisions shall be made to pressurize propellant tanks of Tug to avoid implosion during return flight.

3.5.3 Systems Safety Requirements

a. Tug propellant tank and pressure vessel design factors of safety shall be as specified in Space Shuttle System Payload Accommodations (Ref. 4). Fatigue criteria shall be based on life cycle requirements for individual Tug.

b. Pressure vessels and tanks shall conform with and be maintained under a fracture mechanics control program.

c. Tug shall not have structures that depend on tank pressure for structural stabilization where Shuttle damage could result if the tank pressurization were lost.

d. Provision shall be made to detect incipient failures of tanks containing hazardous fluids or high pressures to the greatest extent possible.

e. A redundant relief capability shall be provided for the Tug tanks which automatically limits the maximum pressure.

f. Tug propellant drain and vent interface with the Orbiter shall permit main propulsion system propellant venting, and emergency detanking (whether Orbiter is in horizontal or vertical attitude) until launch commit, with the Orbiter payload bay doors opened or closed and latched.

g. A capability shall be provided for the Orbiter crew to dump hazardous Tug fluids and vent Tug pressurants overboard within the time constraints imposed by an abort situation. This capability shall be available with the payload bay either open or closed.

h. A capability for remotely controlled expulsion of Tug main propellant tank residuals to space before retrieval operations and pressurization with inert gases shall be provided.

i. To avoid formation of liquid air, the outer surfaces of Tug cryogen tank systems that are exposed to the Orbiter payload bay environment on the ground or in the lower atmosphere shall be at temperatures 90K (-297°F).

j. Tug cryogen tank thermal protection systems shall be designed to minimize (below ignition regimes) accumulation of flammable fluids resulting from propellant system leakage.

k. Leakage sources of the Tug or its equipment shall be minimized by use of all welded or brazed construction where practical.

3.5.4 Reliability Requirements

Tug propellant tank reliability design goals shall include:

a. All subsystems except primary structure and pressure vessels shall be designed to fail safe in the vicinity of the Shuttle Orbiter.

b. All safety subsystems shall be designed to fail operational in the vicinity of the Shuttle Orbiter.

c. Mission critical single failure points will be minimized to the maximum extent possible.

A reliability goal of .97 for all mission phases has been established for use in study and design efforts.

3.6 Maintainability

The Tug propellant tanks shall meet all the maintainability requirements of Ref. 1. Specific propellant tank related maintainability requirements which are to be considered during the lightweight propellant tank design effort are listed below.

3.6.1 Refurbishment

a. The Tug shall achieve reasonable turnaround times and effective mission cost by reducing as much as possible maintenance and inspection of systems, resulting in minimum subsystem replacements between flights.

b. An adequate number of test points will be provided to verify interface integrity and facilitate fault detection and isolation to a line replaceable unit.

3.6.2 Standardization

a. Components and subsystems of the Space Tug will be standardized and reusable.

b. Ground test activities shall use instrumentation systems and sensors required by the flight hardware wherever practical to minimize the requirements for unique ground support equipment.

3.6.3 Interface

Mechanical and structural interfaces between the Tug, ground support equipment, and Shuttle Orbiter will be designed for rapid assembly, alignment, and disassembly.

3.6.4 Testing

a. The capability to quickly establish and verify system readiness will be a prime Space Tug design consideration.

b. System testing during Tug turnaround will be minimized where practicable.

3.7 <u>Ground Support and Transportation</u>

The Tug propellant tanks shall meet all the ground support and transportation requirements of Ref. 1. Specific propellant tank related requirements which are to be considered during the lightweight propellant tank design effort are listed below.

a. The Tug and its ground handling support equipment shall be designed to permit ground, sea and air transport.

b. Transportation and handling equipment shall be designed to ensure that flight structures are not subjected to loads more severe than flight design conditions.

c. The Tug will be transported only in the horizontal position with or without the spacecraft attached.

4.0 STRUCTURAL REQUIREMENTS

4.1 Environment

The Tug propellant tanks shall meet all the conditions of the natural and induced environments of the combined Tug, spacecraft and Shuttle systems during all phases of operation, ground and flight, as specified in References 1, 3, 4, 6 & 7. The following specific environmental requirements which relate to the Tug propellant tanks are to be considered in the lightweight propellant tank design study.

4.1.1 Temperature

The Tug propellant tanks shall be compatible with the flight temperature ranges shown in Table 4.1-1. For ground operations the temperature will be controlled to 297 $\pm$1.7 K (75 $\pm$3 (F) while in the Orbiter Processing Facility. When the Orbiter payload bay doors are closed the payload bay temperature will be controlled to the limits in Table 4.1-1.

Table 4.1-1. Flight Temperature Environment

	Min- K (F)	Max- K (F)
Prelaunch	278 (40)	322 (120)
Launch	278 (40)	339 (150)
On-Orbit (doors closed)	241 (-25)	339 (150)
On-Orbit (doors open)	Tug/SC	Controlled
Tug operations	TBD (1)	TBD (1)
Reentry and Post Landing	241 (-25)	366 (200) (2)

Notes:

(1) Temperatures during Tug operation after deployment are expected to be less severe than the Shuttle environment.

(2) This is a transient end point temperature limit based on a pre-deorbit temperature not exceeding 311 ^{o}K (100^{o}F) with nominal reentry through post landing GSE hookup.

Propellant temperatures to be used for the lightweight tank design are:

LH_2	$20^{\circ}K$ ($-423^{\circ}F$)
LO_2	$90^{\circ}K$ ($-297^{\circ}F$)

4.1.2 Pressure

During Prelaunch and Post Landing operations the payload bay pressure shall not exceed ambient atmosphere pressure plus TBD purge requirements.

The Orbiter payload bay is vented during the launch and entry phases, and operates unpressurized during the orbital phase of the mission. The payload bay pressure history during ascent is shown in Figure 4.1-1. The payload bay reentry pressure history for a typical reentry is shown in Figure 4.1-2.

4.1.3 Vibration

The vibration spectrum that the Tug is expected to experience during ground handling and transportation is a minimum of four sweeps at 1/2 octave per minute at the levels (sinusoidal motion) shown in Table 4.1-2.

Table 4.1-2
Ground Handling & Transportation Vibration Environment

Frequency	Level
2-5 hz	2.5 cm (1.0 in) double amplitude
5-26 hz	1.3g peak
26-500 hz	0.91 cm (0.36 in) double amplitude
500-1000 hz	5g peak

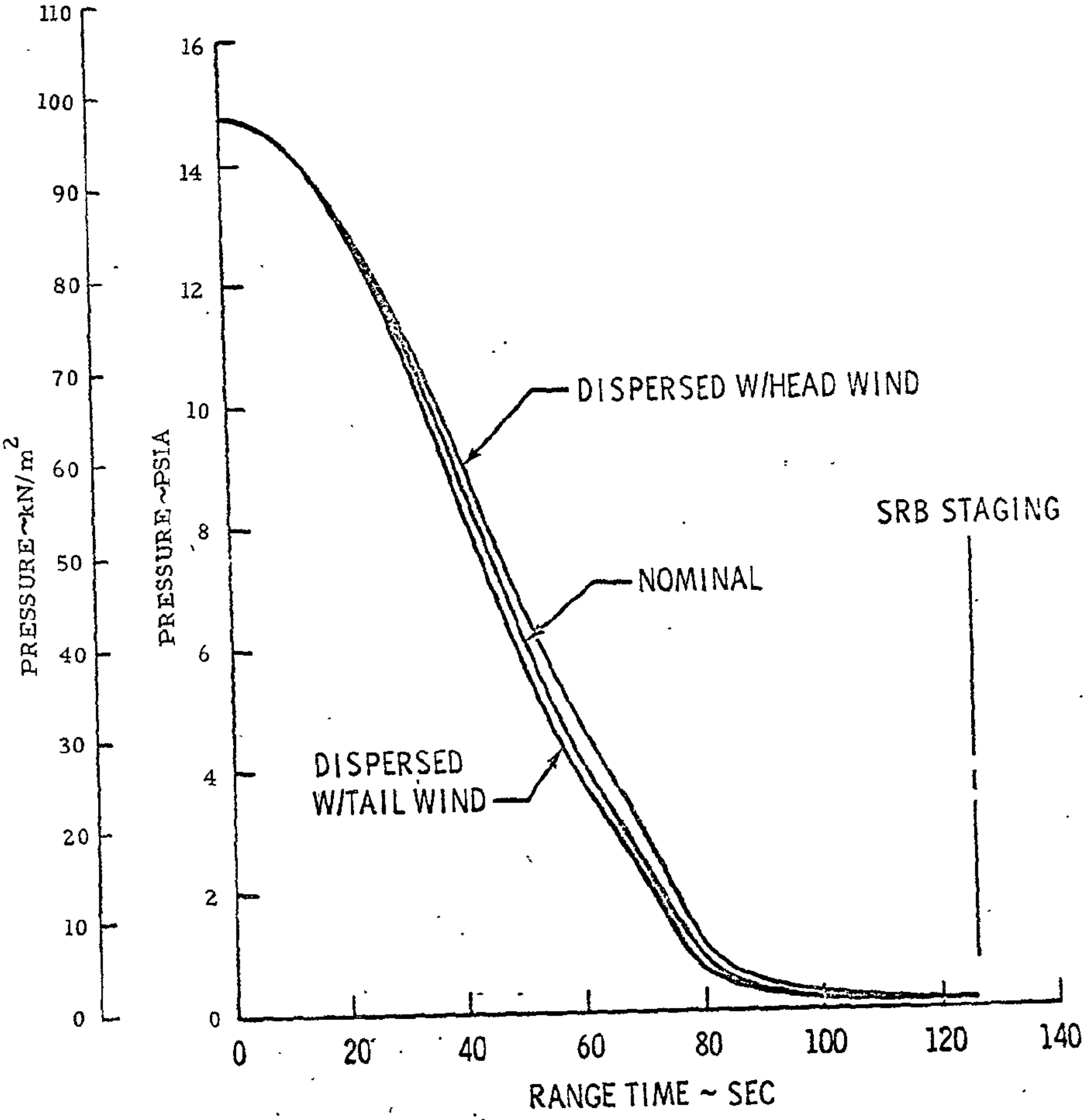


FIGURE 4.1-1 ORBITER PAYLOAD BAY INTERNAL PRESSURE HISTORIES DURING ASCENT

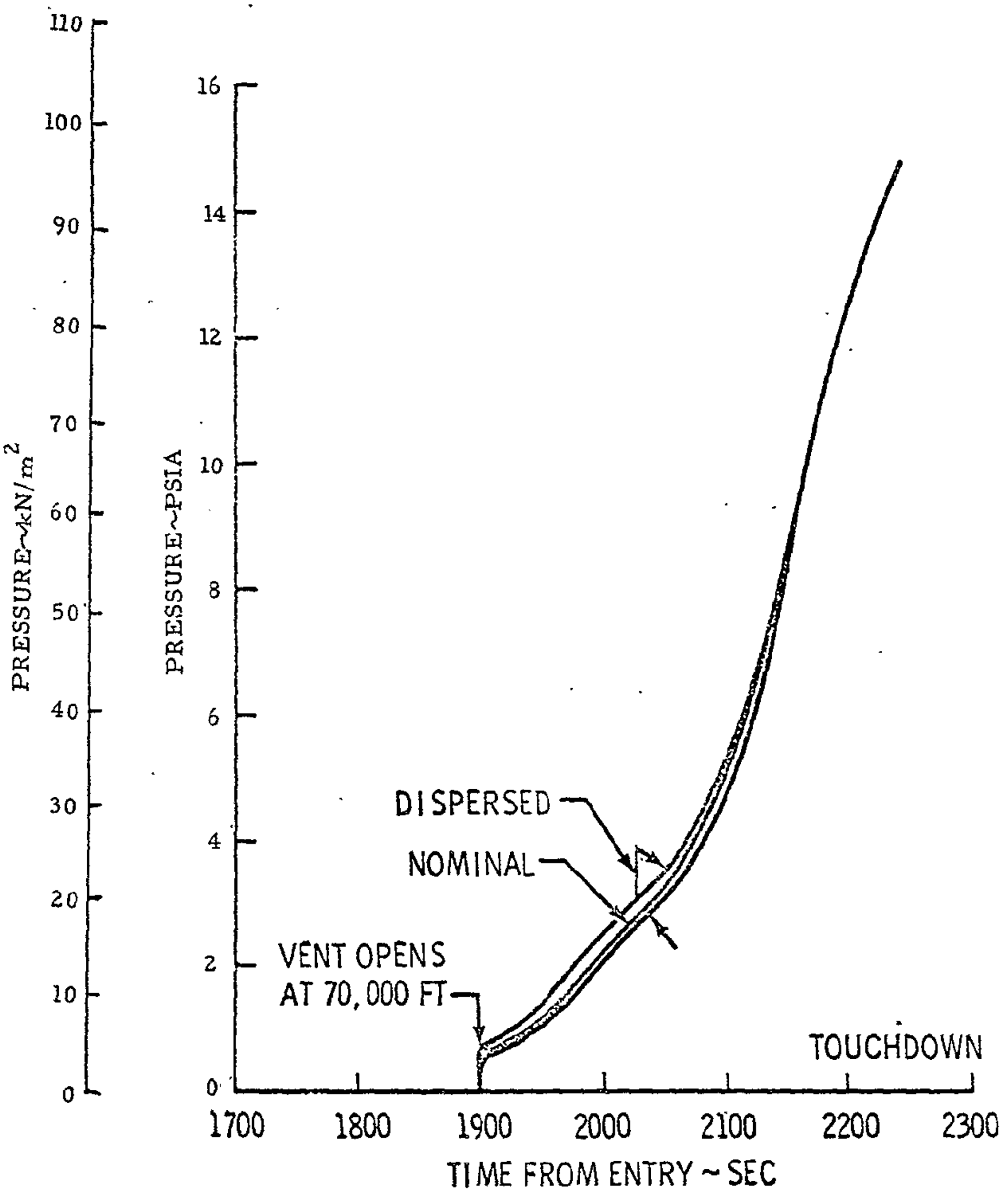


FIGURE 4.1-2 ORBITER PAYLOAD BAY INTERNAL PRESSURE HISTORIES DURING ENTRY

The Space Shuttle vehicle will be subjected to fluctuating pressure loading by engine exhaust generated acoustic noise and flow generated aerodynamic noise. These fluctuating pressure loads are the principle source of structural vibration during flight operations. The estimated random vibration levels at the Tug/Orbiter interface are shown in Figure 4.1-3. These vibration levels exist for approximately 29 sec. per mission. For purposes of tank design the Shuttle on-orbit, Tug operation and reentry vibration environment is negligible.

4.1.4 Shock

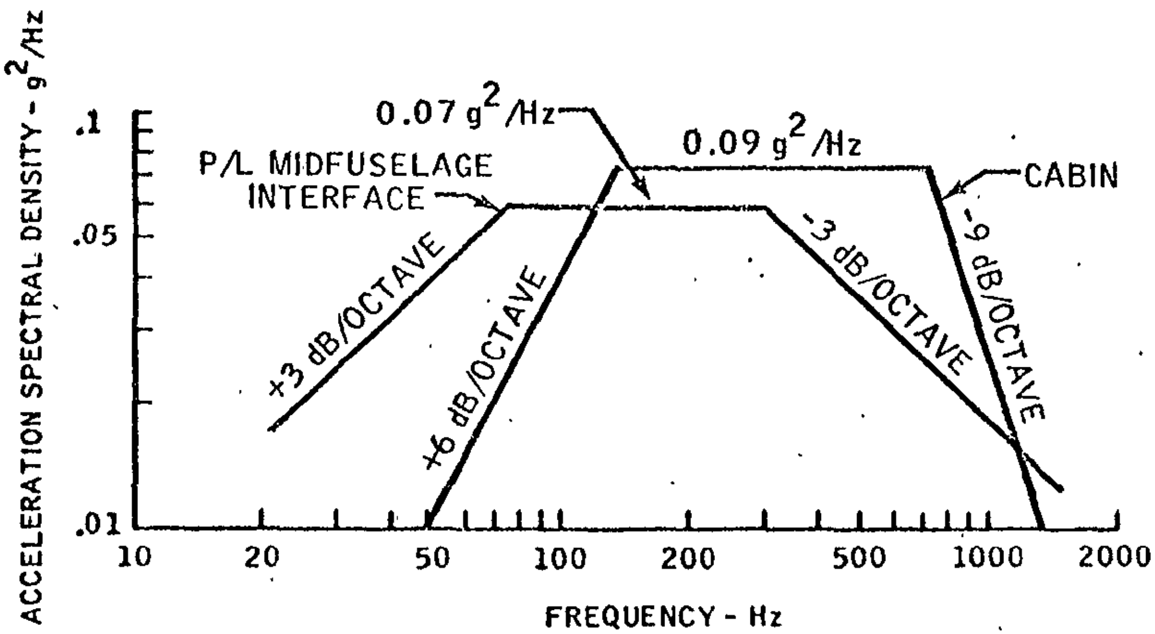
During ground handling the shock environments experienced by the Tug are 20g terminal saw tooth shock pulses of a 10 millisecond duration in each of 6 axis. During transportation the shock environment as simulated by sinusoidal impulses in the frequency range from 3 to 5 kz controlled to one inch double amplitude displacement.

During flight the maximum expected shock environment is:

a. Pyro Shock. (TBD)

b. Landing Shock. Rectangular pulses of the peak accelerations shown in Table 4.1-3 will be experienced by the Tug:

ACTUAL VIBRATION INPUT TO PAYLOADS WILL DEPEND ON TRANSMISSION CHARACTERISTICS OF MIDFUSELAGE - PAYLOAD SUPPORT STRUCTURE AND INTERACTIONS WITH EACH PAYLOAD'S WEIGHT, STIFFNESS, AND C.G.



THESE LEVELS ARE TYPICAL OF LIFTOFF, TRANSONIC AND MAX Q FLIGHT

FIGURE 4.1-3 - Random vibration at payload midfuselage interface and in cabin

Table 4.1-3

Landing Shock Environment

Acceleration (g peak)	Duration (milliseconds)
0.23	170
0.28	280
0.35	330
0.43	360
0.56	350
0.72	320
1.50	260

c. **Crash.** The design goal for crash safety shock is 40g $\pm$ 6g sawtooth for an 11 millisecond duration. Equipment and structure attachments must withstand the crash safety shock without breaking loose and creating a hazard to personnel.

4.1.5 Acoustic

The estimated Shuttle payload bay acoustic spectra generated by the engine exhaust and aerodynamic noise are shown in Figure 4.1-4. The estimated time history of the payload bay overall internal noise level are shown in Figure 4.1-5. The sound pressure levels are overall spatial averages.

4.1.6 Acceleration

Maximum ground handling acceleration (hoisting) for the Tug is 2g vertical within a plus or minus cone angle of 0.35 rad (20 deg). Acceleration

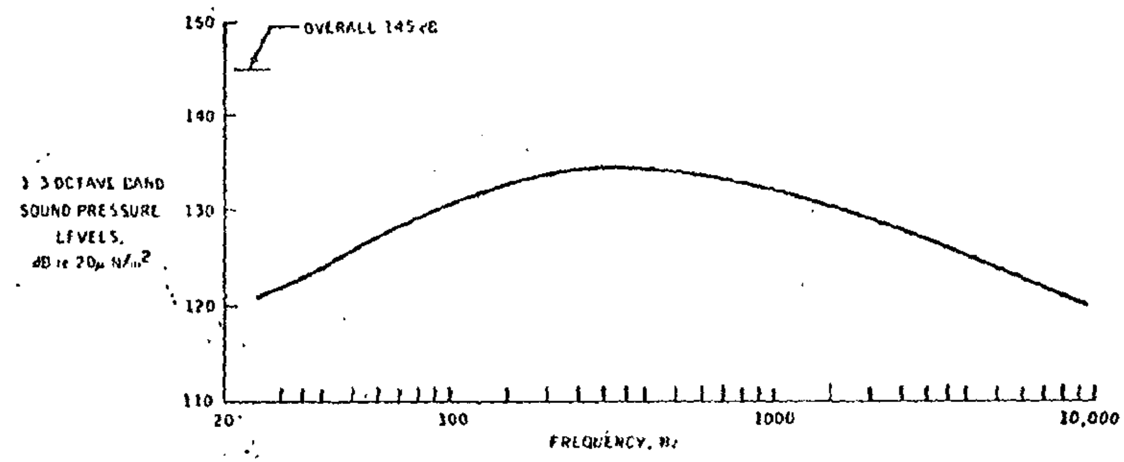


FIGURE 4. 1-4. -- Analytical predictions maximum orbiter payload bay internal acoustic spectra

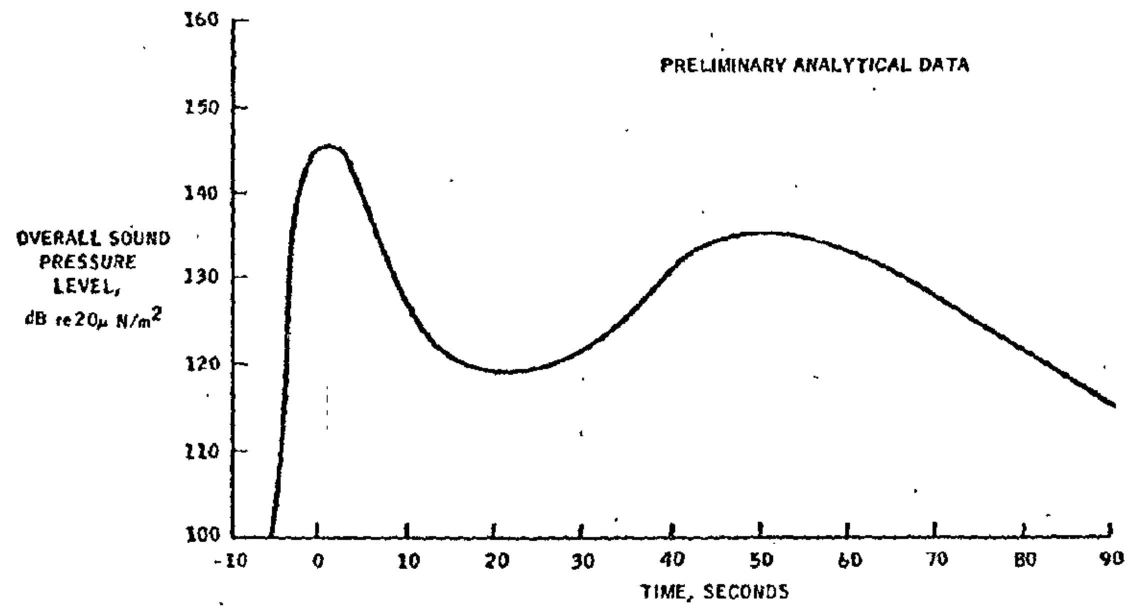


FIGURE 4. 1-5. - Orbiter payload bay internal acoustic time history

during transportation are less critical than the flight accelerations in Table 4.1-4.

Tug flight accelerations while in the Shuttle Orbiter cargo bay from Ref. 11 are shown in Table 4.1-4. These accelerations shall be used for the lightweight propellant tank design study. Accelerations during Tug operations are less critical than the Shuttle accelerations in Table 4.1-4.

4.1.7 Natural Environment

The Tug propellant tanks shall be capable of meeting performance requirements during and after exposure to the natural environments encountered during all phases of the mission as defined in Ref. 3 and 7. Of the natural environments defined in Ref. 3 & 7 radiation and meteroid are the most important for Tug design. Of these, only the meteroid environment has been identified as a significant consideration for the lightweight propellant tank design study.

The Space Tug propellant tanks shall be designed for a .995 probability of no puncture during the maximum total time in orbit including time in the Orbiter with the payload bay doors open using the meteroid model of Ref. 7. For the lightweight propellant tank analysis this total time in orbit shall be assumed to be 8400 hours.

Effects of meteroid shielding by the Tug structure, insulation purge bag, spacecraft, engine, etc., will be considered in the propellant tank meteroid penetration analysis.

TABLE 4.1-4

PAYLOAD LOAD FACTORS (g's) AND ANGULAR ACCELERATION (RAD/SEC²)

Condition	N_X (+ Aft)	N_Y (+ Right)	N_Z (+ Up)	$\ddot{\phi}$ (+ Rt. Wing Up)	$\ddot{\theta}$ (+ Nose Up)	$\ddot{\psi}$ (+ Nose Left)
Liftoff	-1.6±1.3	±0.7	-.1±1.0	±0.15	±0.1	±0.1
Total Payload						
Payload Component						
Simple Support	-1.6±1.3	±0.8	-.1±1.0	±0.15	±0.1	±0.1
Cantilever	-1.6±1.3	±1.0	-.1±1.5	±0.15	±0.15	±0.15
High Q Boost	-1.8±0.2	±0.5	±0.6	±0.15	±0.1	±0.1
Boost Max. Load Factor	-3.0±0.15	±0.2	-0.3	±0.1	±0.1	±0.1
Orbiter Max. Load Factor	-3.0±0.15	±0.2	-0.75	±0.1	±0.1	±0.1
Entry and Descent						
+ Pitch Maneuvers	1.1	0	2.5	0	-0.1	0
- Pitch Maneuvers	0.6	0	-1.0	0	0.7	0
± Yaw Maneuvers	1.0	±1.25	1.0	0	0	±0.2
± Roll Maneuvers	0.9	±0.2	1.5	±2.6	0.3	±0.2
Landing						
Total Payload	-0.2±1.3	±0.7	2.0±1.3	±0.2	±0.2	±0.1
Payload Component						
Simple Support	-0.2±1.3	±0.8	2.0±2.0	±0.2	±0.2	±0.1
Cantilever	-0.2±1.3	±1.4	2.0±5.0	±0.2	±0.4	±0.2
Crash (Ultimate)	+9.0	±1.5	$\begin{cases}+4.5\\-2.0\end{cases}$			

4.2 Loads

Design loads for the Tug propellant tanks include tank, propellant, and equipment inertia loads, internal tank pressure, engine thrust loads, and thermal loads. For the lightweight propellant tank design study, loads from these various sources shall be combined in the most conservative manner consistent with rational phasing of mission events. Propellant tank design shall consider the effects of load reaction and redistribution through the flexible Tug body structure and Tug support system.

4.2.1 Inertia Loads

The Tug propellant tanks will be sized primarily by combined flight inertia and pressure loads. The only ground handling and transportation loads to be considered in the lightweight tank study are those due to the design hoisting accelerations specified in Section 4.1.6. The design flight accelerations from 4.1.6 (Table 4.1-4) shall be used for design of the Tug propellant tanks. Propellant status for each of the critical load events is shown in Table 4.2-1.

Mass properties for major system components mounted on the propellant tanks are tabulated in Table 4.2-2. These components shall be included in the total mass properties of the tanks when calculating critical inertia loads. Propellant densities from Figure 4.2-1 shall be used for propellant inertias.

Table 4.2-1

Propellant Status for Critical Load Events

Condition	Propellant Status LH_2 Tank	LO_2 Tank
Liftoff	Full	Full
Total Payload		
Payload Component		
Simple Support		
Cantilever		
High Q Boost		
Boost Max. Load Factor		
Orbiter Max. Load Factor	Full	Full
Entry and Descent	Empty	Empty
+ Pitch Maneuvers		
- Pitch Maneuvers		
$\pm$ Yaw Maneuvers		
$\mp$ Roll Maneuvers		
Landing		
Total Payload		
Payload Component		
Simple Support		
Cantilever		
Crash (Ultimate)	Empty	Empty

TABLE 4.2-2

Tug Propellant Tank System Component Weights

System Component	LH_2 Tank kg	(lb)	LO_2 Tank	
Feed, Fill & Drain	59	(131)	57	(125)
Pressurization and Vent	24	(54)	20	(44)
Propellant Level and Monitoring	12	(26)	11	(24)
Thermal Control	93	(205)	57	(125)
Main Propulsion	N/A		442	

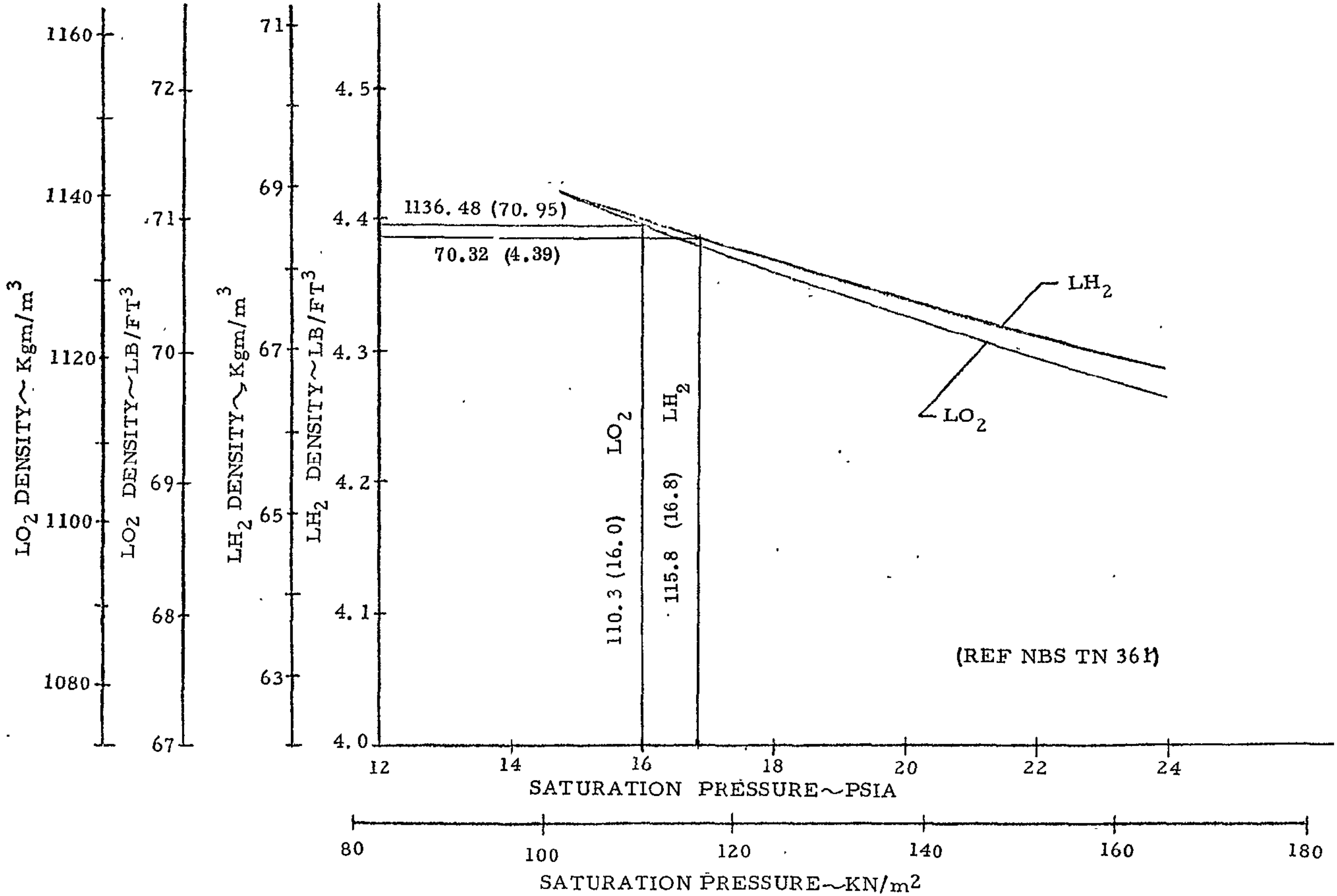


FIGURE 4.2-1 TUG PROPELLANT DENSITIES

4.2.2 Internal Pressure Loads

Maximum design ullage pressure for the Tug LH_2 tank is 137.2 KN/m^2 (19.9 psia). Maximum design ullage pressure for the Tug LO_2 tank is 151.7 KN/m^2 (22.0 psia). These maximum ullage pressures are to be combined with fluid inertia head pressures to design the tanks. Fluid head pressures shall be based on the accelerations in Table 4.2-1. During ascent and descent through the atmosphere the atmospheric pressures shown in Figures 4.1-1 and 4.1-2 shall be used to determine the differential pressure across the tank walls.

The operating pressure range for each tank as controlled by the pressurization and vent/relief systems is shown in Figure 4.2-2.

LH_2 Tank

Ultimate Design Pressure	192 KN/m^2
Maximum Relief Valve Pressure	151.2 KN/m^2
Relief Valve Tolerance Band	(13.8 KN/m^2)
Proof Pressure	144 KN/m^2
Maximum Regulator Pressure (Maximum Operating Pressure)	137.4 KN/m^2
Regulator Tolerance	(6.9 KN/m^2)
Minimum Regulator Pressure	130.5 KN/m^2
Delta Pressure for MES	(14.5 KN/m^2)
Tanking Pressure (Minimum Regulated Pressure)	116 KN/m^2

LO_2 Tank

Ultimate Design Pressure	212 KN/m^2
Maximum Relief Valve Pressure	165.2 KN/m^2
Relief Valve Tolerance Band	(13.8 KN/m^2)
Proof Pressure	159 KN/m^2
Maximum Regulator Pressure (Maximum Operating Pressure)	151.4 KN/m^2
Regulator Tolerance	(6.9 KN/m^2)
Minimum Regulator Pressure	144.5 KN/m^2
Delta Pressure for MES	(34.5 KN/m^2)
Tanking Pressure (Minimum Regulated Pressure)	110 KN/m^2

Figure 4.2-2

Tug Propellant Tank Operating Pressure Range

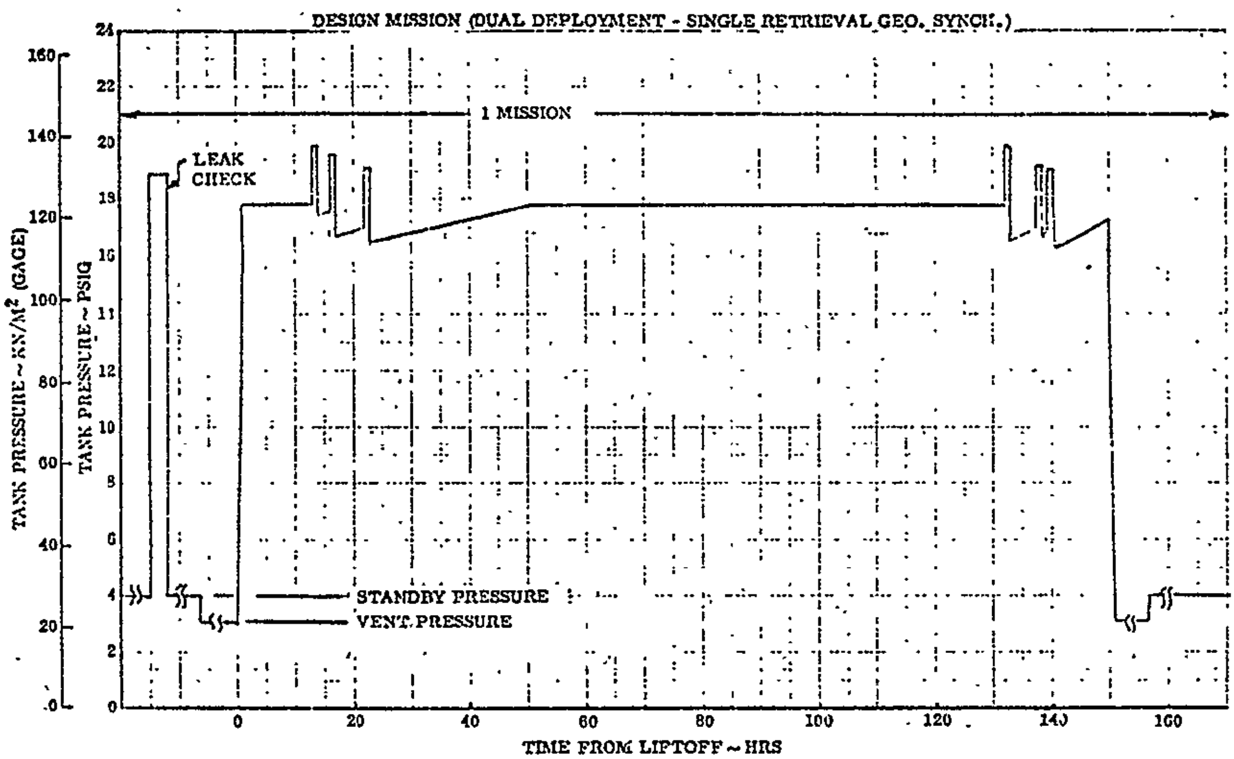
A typical mission pressure profile for the Tug LH_2 and LO_2 are shown in Figure 4.2-3. These pressure profiles shall be assumed typical for the entire 50 mission life of the Tug for purposes of preliminary fatigue and fracture mechanics analysis of the propellant tanks.

4.2.3 Engine Thrust Loads

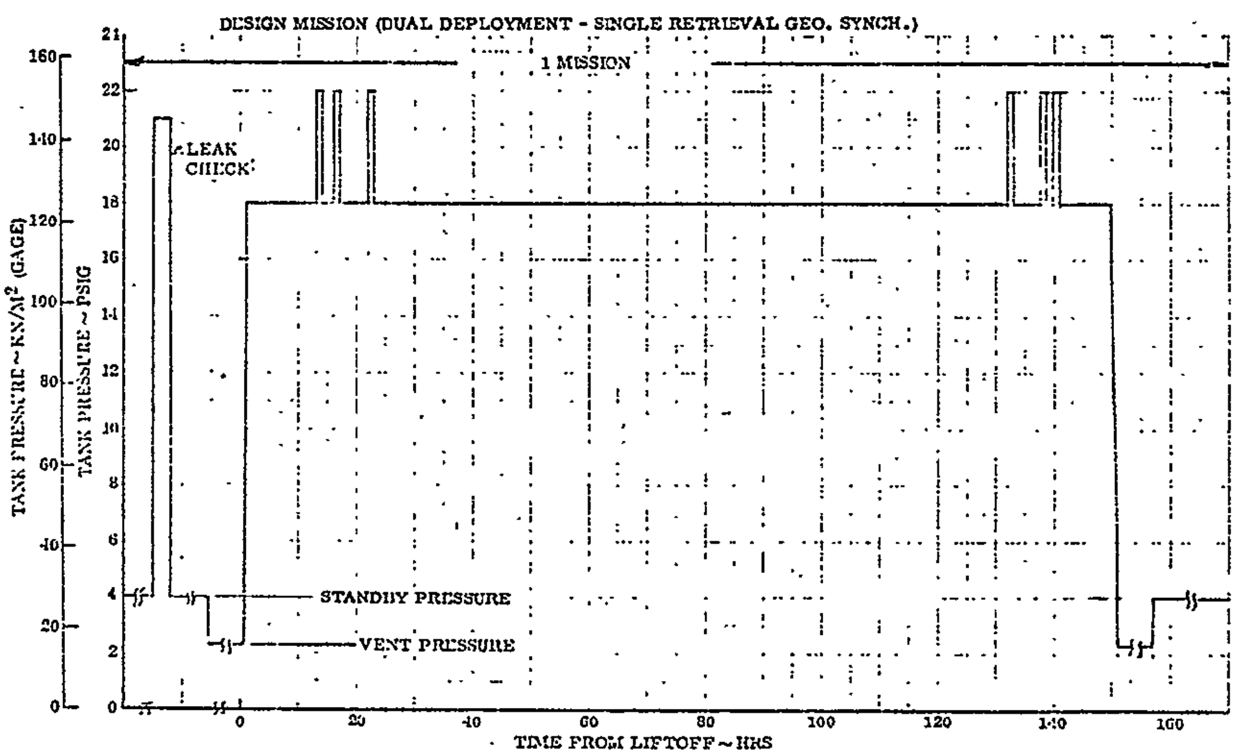
The Tug LO_2 tank shall be designed to support the 66720 N (15000 lb) maximum thrust load of the RL 10 Cat IIB main engine including the effects of maximum engine gimbal angle. Maximum gimbal angle is .05 radians (3 degrees in each of the Y and Z directions (square gimbal pattern).

4.2.4 Thermal Loads

The Tug propellant tanks shall be designated to accommodate structural thermal loading due to all transient thermal events and temperature gradients. These thermal loads shall be combined in the most conservative manner with all other maximum propellant tank loads consistent with rational phasing of mission events. Thermal loads shall be determined as a result of a detailed thermal analysis of the propellant tanks and adjacent Tug structure.



LH_2 Tank Design Pressure Profile.



LO_2 Tank Design Pressure Profile.

Figure 4.2-3

Tug Propellant Tank Typical Mission Pressure Profiles

4.3 Factors of Safety

The factors of safety specified in Table 4.3-1 are the minimum to be applied to combined stresses for the design of Tug propellant tanks. For components or systems subjected to several missions, safety factor requirements shall apply to all missions. Consideration shall be given to transient loads and pressures, such as surge phenomena, when required.

In circumstances where certain loads have a relieving, stabilizing, or otherwise beneficial effect on structural load capability, the minimum expected value of such loads shall be used and shall not be multiplied by the factor of safety in calculating the design-yield or ultimate load. For example, the ultimate compressive load in pressurized vehicle tankage shall be calculated as follows:

Ultimate Load - Safety Factor X Body Loads - Minimum Expected Pressure Load

When a pressurized system or component is subjected to external loads, such as inertia, air loads, ground handling, transportation

Table 4.3-1
Tug Propellant Tank Factors of Safety

1. General Safety Factors

Manned Environment

Yield Factor of Safety	= 1.10
Ultimate Factor of Safety	= 1.40

Unmanned Environment

Yield Factor of Safety	= 1.10
Ultimate Factor of Safety	= 1.25

2. Safety Factors for Pressures

a. Propellant Tanks

Manned Environment

Proof Pressure	= 1.05 x limit pressure
Yield Pressure	= 1.10 x limit pressure
Ultimate Pressure	= 1.40 x limit pressure

Unmanned Environment

Proof Pressure	= 1.05 x limit pressure
Yield Pressure	= 1.10 x limit pressure
Ultimate Pressure	= 1.25 x limit pressure

b. Hydraulic and Pneumatic Systems, including reservoirs

(1) Lines and Fittings, less than 1.5 inch diameter

Proof Pressure	= 2.0 x limit pressure
Ultimate Pressure	= 4.0 x limit pressure

(2) Lines and Fittings, 1.5 inch diameter or greater

Proof Pressure	= 1.2 x limit pressure
Ultimate Pressure	= 1.5 x limit pressure

(3) Hydraulic and Pneumatic Tanks & High Pressure Vessels

Proof Pressure	= 1.5 x limit pressure
Ultimate Pressure	= 2.0 x limit pressure

(4) Actuating Cylinders, Valves Filters, Switches

Proof Pressure	= 1.5 x limit pressure
Ultimate Pressure	= 2.0 x limit pressure

in addition to pressure, the general factors of safety given in Table 4.3-1 shall be used. That is, the pressure vessel thickness is determined by the use of applicable pressure factors from Table 4.3-1 and then the component is analyzed for the combined external loads, pressures, and environments with the general safety factors. The pressure factors of safety shall not be used in combination with the general factors.

4.3.1 Proof Pressure Factors

Fracture mechanics analyses shall be performed to establish the proof pressure factor required to determine the maximum possible flaw size for verification of service life with respect to the cyclic and sustained load history. The proof factor to be used shall be the larger of the factors (a) specified in Table 4.3-1, or (b) determined by fracture mechanics analyses. To determine proof factors for temperatures other than use temperatures, use the following equation:

$$\text{Proof Factor (Test Temp)} = \left[\frac{K_{IC} \text{ at Test Temp.}}{K_{IC} \text{ at Use Temp.}}\right] \text{Proof Factor (Use Temp)}$$

4.3.2 Fatigue Factors

a. All structural elements shall be evaluated for their capability to sustain any cyclic load conditions which are part of the design environment. For those elements whose design is controlled by a cyclic or repeated load condition, or a randomly varying load condition, fatigue analysis shall be performed.

b. Structures and components shall be designed and tested to demonstrate the following factors based on guaranteed minimum life.

   a. Low Cycle Fatigue 4 (on cycles)

   b. High Cycle Fatigue 10 (on cycles)

c. A detailed design life cycle history shall be developed in sufficient detail that a cumulative damage assessment can be analytically verified for each major structural component of the structural and propulsion systems and the engines. In general, these data can be shown by a component load history profile showing usage cycles, load intensities, and environments.

d. For cyclic loads to varying levels, such standard methods as Miner's Method shall be used to determine the combined damage. For repeated load combined with a steady load, such standard methods as the Modified Goodman Diagram shall be used to determine the combined effect.

4.3.3 Ground Handling and Transportation Factors

As a design goal, flight structure design shall be based on flight design and conditions rather than on transportation and handling loads. Transportation equipment design shall ensure that flight structures are not subjected to loads more severe than flight design conditions.

Transportation loads are a function of the transportation mode. Transportation loads shall include the steady state loads plus dynamic, vibration, and shock loads determined by analysis based on the mode of transportation.

4.4 Material Requirements

Materials used for the Tug propellant tank shall, in addition to having good structural efficiency, have all of the following characteristics:

a. good fracture toughness

b. high stress corrosion resistance

c. good weldability

d. compatibility with the propellants

e. compatibility with the operating temperatures

f. well characterized properties

Tank material mechanical and physical properties used in the lightweight tank design study shall be based on existing published data from approved sources such as MIL-HDBK-5B wherever possible. Additional materials tests shall be used to augment this data where required. Properties at cryogenic and elevated temperatures as well as room temperature shall be defined. Use of cryogenic allowables for tank design is permissible if their use is compatible with all the operational, functional and structural requirements for the tanks.

4.5 Stiffness Requirements

To minimize dynamic coupling between the Tug and Shuttle it shall be a design goal to maintain the first lateral cantilever node of the Tug/spacecraft above 5 hz. To meet this requirement it shall

be a preliminary design goal to maintain the first lateral mode frequency of the Tug propellant tanks (relative to a rigid Tug body structure) above 10 hz. The first mode longitudinal frequency for the propellant tanks shall be maintained above 10 hz. The propellant tank support system, main engine support system, tank support bracketry, etc. shall be sized as required to meet these stiffness requirements.

4.6 Fracture Control

A fracture mechanics analysis shall be performed on each of the Tug main propellant tanks to demonstrate the structure will withstand the limit loads, pressures and operating environments throughout its service life without detrimental deformations, leakage, or brittle fracture from hidden flaws.

A detailed fracture control plan shall be generated for each tank including fracture criteria, a fracture mechanics analysis, inspection requirements, and testing requirements.

For the lightweight propellant tank design, the fracture mechanics analysis shall establish the required proof pressure ratios and the maximum operating stress levels to ensure internal flaws do not grow to the critical crack length or through the tank thickness during the tank design life.

Service life for the Tug propellant tanks shall be 50 missions. As specified in Section 4.3 the service life shall be multiplied by a factor of 4.0 to obtain the design life for fracture analysis. The absolute

pressure profiles shown in Figure 4.2-3 shall be assumed for each mission. These profiles are based on the Tug propellant tank absolute pressure profiles for a typical 6 burn mission. They must be corrected for ambient pressure to obtain the differential pressures acting across the tank walls during the mission. A ambient helium leak check pressure cycle is to be assumed prior to each mission. The leak check is performed at the nominal pressure of 130 ± 7 KN/m^2 (18.9 ± 1 psid) for the LH_2 tank and 145 ± 7 KN/m^2 (21.0 ± 1 psid) for the LO_2 tank.

A proof test methodology which includes propellant inertia head effects shall be developed for each tank. The total pressure profile shall include a single proof test (which may consist of multiple cycles on each tank. Nominal standby pressure during ground operations is 27.6 ± 7 KN/m^2 (4.0 ± 1 psid) for both tanks. Total design life for each tank is 8400 hours.

5.0 TESTING

The propellant tank test and checkout philosophy and requirements correlate directly with the Tug program requirements for mission reliability (97%) and useful life and the vehicle's designed-in capability to meet those requirements. The approach is that of minimum overall test and checkout without degrading required reliability. The major testing activities include:

Development

Qualification

Acceptance

Prelaunch

Operational

Post Launch

Post Flight and Post Maintenance

5.1 Development

Development tests are performed to verify the feasibility of the selected design approach, evaluate hardware performance, and to evaluate failure modes and safety factors for qualification of flight hardware and ground support equipment (GSE). This includes requirements for:

a. Components and subsystems testing

b. Structural testing

c. Dynamic testing

d. System compatibility testing

e. Combined systems test

The propellant tank test articles required during development include:

a. A structural test article (STA).

b. A propulsion test vehicle (PTV).

c. Various components and subsystem articles not previously developed and/or qualified.

Specific development tests are TBD.

5.2 Qualification

Qualification testing is the basis for verifying that the propellant tanks meet the performance and design requirements under greater than anticipated operational environments. This includes verification of design margins sufficient to meet all mission requirements.

Specific qualification tests are TBD.

5.3 Acceptance

Acceptance tests are required to verify acceptance of Space Tug propellant tanks by confirming that each tank conforms to specifications of previously qualified items. They are also performed to verify that handling and/or assembly has not caused physical or functional damage, and that the completed tank assemblies are compatible with other Space Tug systems. The following acceptance tests will be performed on each tank:

a. Leakage and functional tests

b. Proof pressure test

c. Alignment Verification

d. Weight and center of gravity determination

e. Environmental tests

f. Subsystem acceptance tests

5.4 Operational

Test and checkout for the operational phase commences with new Tug inspection and functional checkout and concludes at the end of the first operational cycle with post refurbishment checkout. The pre-mission requirements for testing vary according to the vehicle condition and the maintenance actions performed.

Following receipt of a new Tug from the manufacturer, the vehicle undergoes a comprehensive visual inspection for shipping and handling damages. Leak checks are made using ultrasonic leak detection methods, mass spectrometry, or pressure decay methods to determine the seal integrity of valves, lines, and tanks.

Specific operational tests requirements for the Tug propellant tanks are TBD.

5.5 <u>Prelaunch</u>

Specific prelaunch test and checkout requirements for the Tug propellant tanks are TBD.

5.6 Post Landing

During post landing test and checkout the propellant and pressurization systems are checked following purge for safe condition prior to moving to the Orbiter facility for demate. Specific post landing test and checkout requirements for the Tug propellant tanks are TBD.

5.7 Post Flight and Post Maintenance

Following demate and transport to the Tug facility, the propellant tanks are subject to an inspection for system deterioration and structural defects and damage. After each flight a leak check will be performed on each propellant tank using ambient helium. The LO_2 tank will be pressurized to 145 $\pm$7 KN/m^2 21 $\pm$ 1 psid) and the LH_2 tank will be pressurized to 131 $\pm$ 7 KN/m^2 (19 $\pm$1 psid) for the leak checks.

6.0 REFERENCE DOCUMENTS

1. MSFC 68M00039-1 - Baseline Space Tug - System Requirements and Guidelines
2. MSFC 68M00039-2 - Baseline Space Tug - Configuration Definition
3. NASA TMX 64713 - Natural Environment Design Requirements
4. JSC 07700 Vol. XIV, Rev. C - Space Shuttle System Payload Accommodations
5. MSFC-HDBK-505 - Structural Strength Design and Verification Program Requirements
6. NASA TM-X64627 - Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development
7. SP 8013 - Meteroid Environment Model - 1969
8. CASD-NAS75-017 - Space Tug/Shuttle Interface Compatibility Study - Final Report
9. CASD-NAS73-033 - Space Tug Systems Study (Cryogenic) - Final Report
10. Level II PRCBD 500273A - Change Request to JSC 07700 Vol X
11. MSFC PFO2-75-31 - Space Tug/Orbiter/Interface Compatibility Study - Space Tug Acceleration Factors
12. NAS8-3101 (MCR-74-488) - Tug Fleet and Ground Operations Schedules and Controls

APPENDIX B

TEST TANK

FRACTURE CONTROL PLAN

PD 75-0065

CONTRACT NAS8-31370

FRACTURE CONTROL PLAN

LIGHTWEIGHT LO_2 AND LH_2 PROPELLANT TANKS

GENERAL DYNAMICS

Convair Division

FOREWORD

This plan is representative of a Fracture Control Plan for the Tug tankage system. For purposes of test tank design and manufacture only, the applicable sections will be used as identified on the manufacturing drawings.

CONTENTS

FIGURES

1

OBJECTIVES

The purpose of this Fracture Control Plan is to identify, define, and assign responsibility for all tasks necessary to ensure that lightweight LO_2 and LH_2 propellant tanks comply with the service life and residual-strength requirements of Reference 1. More specifically, these tasks are aimed at:

a. Prevention of failure that would cause loss of the space vehicle or injury to personnel due to growth of undetected flaws or cracks in the main propellant tanks.

b. Minimizing vehicle down-time and refurbishment costs due to repair or replacement of a leaking tank.

These requirements are based on the design criteria for the Space Tug main propellant tankage system.

2

DESIGN REQUIREMENTS

In its strictest sense, the term Fracture Control is concerned with loss of structural integrity through growth of flaws. However, since static strength and fatigue life of the "unflawed" structure are also essential to the structural performance of the vehicle, some description of these requirements is included below. The term "unflawed" is used here to denote a structure effectively free of flaws that would degrade the static and fatigue behavior of its materials below accepted design values.

2.1 STATIC STRENGTH OF "UNFLAWED" STRUCTURE

Static strength will be provided in the propellant tank structure to carry any design loads expected during the service life of the Space Tug, under the appropriate environmental conditions, assuming an "unflawed" structure. The ultimate design loads will be arrived at by combining, in a rational manner, the effects of externally applied loads, thermally induced loads, and pressure loads, using the appropriate ultimate factors of safety. The structure will be designed and constructed to be capable of carrying these ultimate design loads without failure. In addition, the structure will sustain all limit design loads without yielding or excessive deformation, including creep in those structural elements which experience long duration elevated temperatures.

2.2 FATIGUE DURABILITY OF "UNFLAWED" STRUCTURE

The "unflawed" structure will be shown by analysis and/or test to withstand the design fatigue spectrum loading equivalent to four service lifetimes without fatigue failure.

2.3 DAMAGE TOLERANCE REQUIREMENTS

It is recognized that all structures contain flaws, defects, or other anomalies which are inherent in the material or are introduced in fabrication, handling, or service.

Conventional inspection procedures will be applied to all propellant tank structural components at various stages of manufacture from material procurement through final tank sell-off, to ensure that these flaws do not exceed acceptable limits of size, character, or number. Elements of the propellant tanks designated as fracture-critical parts (defined in Section 5) will undergo particularly intensive nondestructive evaluation (NDE) to provide statistical assurance that flaws larger than an acceptable maximum size based on the capabilities of the NDE techniques are not present in the as-delivered tank.

The propellant tanks will be designed as safe-life structures, in which potential initial flaws or defects are not allowed to attain critical size required for unstable rapid propagation. In addition, those elements of the propellant tanks which meet the leak-before-break criteria will be designed so that potential initial flaws or defects will not propagate through the material thickness in the Tug design life. The propellant tanks will be shown by analysis to be capable of enduring the design spectrum of cyclic loads corresponding to four times the design vehicle life (DVL), assuming an initial flaw of the most unfavorable type and location, and of the maximum size that can escape detection in detail part NDE. The residual strength required at the end of the DVL is defined as the design limit load or the maximum service spectrum load, whichever is larger.

In the event that significant weight penalties are incurred by the above requirement and the part is readily inspectable in service, a safe inspection period will be recommended, based on the capabilities of the in-service NDE technique. The required safe-life (divided by the scatter factor of 4.0) will then be taken as one inspection period.

3

APPROACH AND IMPLEMENTATION

3.1 FRACTURE CONTROL BOARD

Implementation of the Fracture Control Plan is the responsibility of the Fracture Control Board (FCB), which is charged by the Program Director with the management of all fracture control activities. FCB membership consists of a Chairman, appointed by the Program Director, and representatives of the structural design, structural analysis, materials and processes, quality assurance, material procurement, and production operations functions.

Specific responsibilities of the FCB are:

a. Members are responsible for ensuring that the functional organizations which they represent adhere to the procedures and requirements of this plan and the fracture control requirements of Reference 1, and implement the recommendations of the FCB.

b. Review the propellant tank structural design, materials, and analysis and manufacturing procedures for deficiencies that could have detrimental effect on structural reliability and fracture control. This review will also ensure that good detail design practices are followed to minimize stress concentrations and potential crack-initiation sites, and provide for accessibility, inspectability, and repairability.

c. Review all component parts for fracture criticality, applying the criteria as defined in Subsection 5.6 to select those components, and areas of components, which qualify as fracture-critical (FC) parts. Prepare a list of designated FC parts.

d. Review and approve procedures for fracture control of individual FC parts.

e. Review for adequacy the methods and data used for the analysis of flaw growth in FC parts.

f. Review for adequacy the controls on materials and processes applied to FC parts.

g. Review for adequacy the application and capability of NDE techniques and procedures.

h. Review for adequacy the propellant tank proof test techniques and procedures.

i. Maintain constant awareness of progress against the Fracture Control Plan, and of any problems arising during its implementation. Contribute to, review, and approve solutions to those problems.

j. Maintain records of all FCB actions, including minutes of meetings and all directives issued, and make these records available for customer review as requested.

k. Review and approve all design and manufacturing changes affecting FC parts for their impact on structural behavior.

l. Perform Materials Review Board (MRB) functions in cases of nonconformance involving FC parts.

3.2 FUNCTIONAL RESPONSIBILITIES AND APPROACHES

Some specific fracture control-related responsibilities of each of the organizations represented on the FCB are identified by function in the following paragraphs.

3.2.1 ENGINEERING

3.2.1.1 Design. Engineering Design will ensure that all FC parts are designed using sound and established design practices, paying particular attention to:

a. Use of damage-tolerant design concepts and materials.

b. Avoidance of eccentricities and stress concentrations that could act as crack nuclei.

c. Provision of access and clearance wherever possible to facilitate inspection and maintenance of FC parts.

All fracture-critical parts, and parts containing fracture-critical areas, will be identified on engineering drawings. In addition to designating that portion of the part which is fracture-critical, the drawings shall specify special requirements for materials, processes, and quality assurance methods and acceptance standards.

3.2.1.2 Materials and Processes. Selection of materials for FC parts and the processes involved in their fabrication, joining, cleaning, heat treating, inspection, and finishing will require the participation of Engineering Materials and Processes. Fracture control considerations will be an integral part of the materials and processes selection task to ensure that the fatigue and crack growth characteristics of the selected material are optimized, taking into consideration strength, the effects of stress corrosion, fabrication and joining processes, temperature, and other environmental factors.

Materials and Processes shall prepare contractor material specifications when fracture control requirements are not adequately imposed by existing government or industry specifications. The specifications shall incorporate any special requirements for fracture control, including NDE techniques and inspection standards, and fracture toughness testing, and shall specify test methods, test specimen configurations, and material sampling plans to verify compliance with these requirements. Where possible, uniform test procedures conforming to recognized standards will be used for determination of material fracture properties.

3.2.1.3 Structural Analysis. Structural Analysis will examine the state of stress and consequence of failure of each structural element, and determine if the part should be classified as fracture-critical in accordance with the selection rationale of Subsection 5.6.

A fracture mechanics analysis that supplements normal structural static and fatigue analyses will be conducted for all primary structure subject to significant tensile

stresses. This evaluation will consider all significant conditions which occur during fabrication and operational phases that may affect fracture behavior, as well as size, character, orientation, and location of initial flaws that could become critical during the service life.

The analysis will include calculations for critical flaw sizes, component safe-life and residual strength, and recommendations of component safe inspection intervals and inspection areas as required.

3.2.2 MATERIAL PROCUREMENT. Purchasing will procure raw materials for fracture-critical parts to the applicable specifications and provide for storage and release of these materials separate from conventional materials. Procurement requirements and controls will be implemented to ensure that suppliers and subcontractors use fracture control procedures and precautions consistent with this Fracture Control Plan and Reference 1.

3.2.3 PRODUCTION OPERATIONS. Production Operations is responsible for the detailed defintion of fabrication techniques to be used in producing fracture-critical parts and for contributing information regarding the type and probable location of defects that may be induced in the structural component by these techniques (based on related experience). They are also responsible for ensuring that both tooling and techniques used in manufacturing are reviewed and approved by the board as acceptable for use with fracture-critical parts.

Manufacturing orders and tooling orders will be clearly identified as applicable to fracture-critical parts, and will be approved by the Fracture Control Board for compliance with the appropriate materials processing documents prior to Manufacturing Planning release.

The designs for tooling, fixtures, and manufacturing aids used on fracture-critical parts shall be compatible with fracture control requirements and objectives. Fracture control aspects to be considered in the design of tooling, fixtures, etc., will include, but are not limited to:

a. Protection of components from damage during hoisting, positioning, transporting, etc.

b. Elimination or minimization of residual stresses during processing.

c. Maintenance of tolerances and meeting of surface finish requirements.

Production Operations will ensure that fabrication processes used on fracture-critical components are in conformance with fracture control requirements as defined in Reference 1. This includes participation in qualification of processes and the certification, qualification, or indoctrination of personnel as required.

3.2.4 QUALITY ASSURANCE. Quality Assurance will attend design review of all parts determined to be fracture-critical, to ensure that all aspects of NDE requirements are considered. These NDE requirements will include determining: (1) the feasiblity of using the NDE method(s) selected for evaluating a fracture-critical part and (2) the capability of the NDE method(s) for detection of unacceptable flaw sizes specified for each fracture-critical part.

Quality Assurance will attend Material Review of fracture-critical parts to ensure that decisions on material or part dispositions are satisfactory. As part of this review cycle, QA will recommend additional NDE as required to verify that material properties meet specification prior to release into the production cycle.

Quality Assurance is also responsible for verifying that fracture control requirements defined by Reference 1 and applicable engineering specifications have been met during production of raw material, in-house and supplier fabrication processes, testing, and operational service, and for maintaining all required documentation pertaining

to fracture control parts, including historical and operational data. This also includes qualification of processes and certification of personnel as required.

3.3 TRACEABILITY

Traceability will be established through serialization and lot identification on all fracture-critical parts. This will permit the determination, by means of historical records, of the variable characteristics for any fracture-critical part contained within any end item. The traceable variable characteristics accessible through the part serial number will encompass the measured properties of the raw material identified by lot number, and extend through all processing and inspection records to the deliverable end item. In addition, all discrepancy documentation will form a part of the record.

4

FLAW DETECTION AND EVALUATION

4.1 ACCESSIBILITY AND INSPECTABILITY PROVISIONS

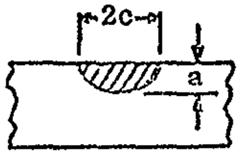
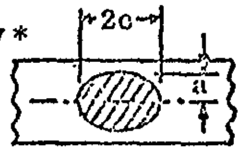
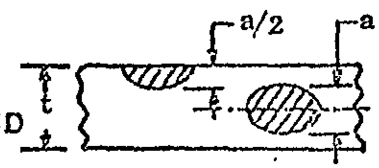
Wherever possible without significant increase in weight or cost, the propellant tank structure will be designed so as to permit access to critical regions at various stages of assembly from subassembly to the flight-ready configuration, for purposes of inspection. The space and clearance requirements of the NDE equipment will be taken into consideration.

4.2 INSPECTION METHODS AND CAPABILITY

Quality Assurance will review the potential initial flaws described on the Engineering documentation of fracture-critical parts to determine optimum NDE technique(s) and equipment to ensure reliable detection. Laboratory testing and evaluation will be performed as required to establish procedures for each specific fracture-critical part.

The capability of the selected NDE technique(s) to reliably detect initial flaws defined by Engineering documentation for fracture-critical components will be verified by tests described below. Quality Assurance shall immediately notify the Fracture Control Board of any case in which it is determined that the best available NDE techniques will not, because of part configuration, accessibility, or other limitation, reliably detect specified initial flaws.

4.2.1 NDE CAPABILITY VERIFICATION TESTS. Tests will be performed on precracked specimens to demonstrate the capability of available equipment and techniques to detect, with a statistical assurance of 90 percent probability and 95 percent confidence, flaws having the sizes, shapes, and orientations shown for "Special NDE" in Figure 4-1.

FLAW TYPE		INSPECTION METHOD	SPECIAL NDE a (inches)	SPECIAL NDE 2c (inches)	STANDARD NDE a (inches)	STANDARD NDE 2c (inches)
SURFACE FLAW		PENETRANT	0.025	0.050	0.075	0.150
EMBEDDED FLAW *		ULTRASONIC	0.024	0.047	0.050	0.100
SURFACE OR EMBEDDED FLAW		RADIOGRAPHIC	a = 60% t		a = 70% t	

* Embedded flaws in rolled aluminum alloy plate are to be considered parallel to surface of plate.

Figure 4-1. NDE flaw detection capability.

Specifically, the tests will demonstrate the ability to:

a. Detect surface flaws with a length of 0.050 inch and depth of 0.025 inch by penetrant inspection.

b. Ultrasonically detect a 3/64-inch flat-bottom hole.

c. Using X-ray, detect material separation (crack) that has penetrated 60 percent of material thickness in fabricated product materials.

An NDE Capability Verification Plan is to be prepared, which decribes detailed procedures for these tests.

4.2.2 DETAIL PART FABRICATION. Fracture-critical detail parts will be inspected using the best applicable NDE methods and techniques. Based upon the capabilities of best NDE methods and techniques, it is assumed that all flaws having dimensions larger than those shown under "Special NDE" for various types of flaws in Figure 4-1 will be detected.

4.2.3 IN-SERVICE INSPECTIONS. The inspection methods and their capabilities for evaluating flaws in tankage systems, after flight, will be developed for any areas that may require in-service inspection.

5

FRACTURE ANALYSIS

5.1 STATIC LOADS AND CYCLIC LOADING SPECTRA

The design loads for which static strength will be provided in the tank structure will be those shown to be critical by the internal load and stress analysis. All design flight and ground loading conditions will be considered, together with the appropriate thermal history, in arriving at net member loads. Fatigue spectra are to cover all significant phases of the baseline missions that make up the Tug service life. These spectra will be used in performing both fatigue analysis and crack growth life analysis of all fracture-critical areas.

5.2 OPERATING AND STORAGE ENVIRONMENTS

The effects of environmental factors, including ambient and induced temperatures, and space vacuum, will be considered in evaluating the structural behavior of propellant tank materials.

5.3 INITIAL FLAW SIZES

For purposes of flaw growth analysis, the maximum size of initial flaws assumed to exist in a structural component will be in accordance with Figure 4-1.

5.4 FRACTURE AND FLAW GROWTH CHARACTERISTICS OF MATERIALS

Material properties required for the fracture mechanics analysis of fracture-critical parts will, if possible, be obtained from standard sources. Where the required design values are not to be found, they will be determined from an appropriate test program.

5.5 FRACTURE ANALYSIS METHODS

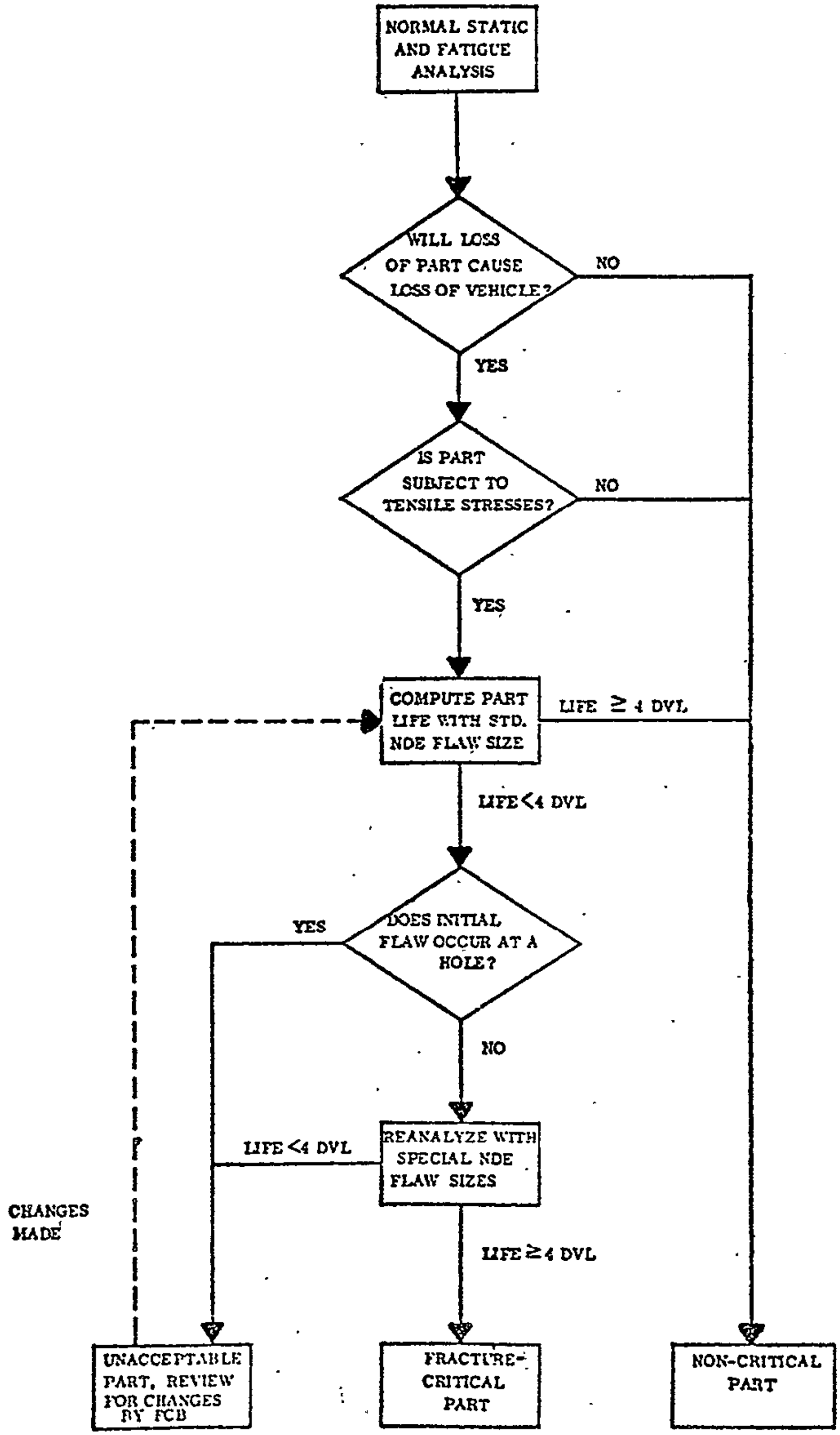
A crack growth predictive analysis method such as the RI/SD FLAGRO program is to be used for the propellant tank fracture analysis.

5.6 FRACTURE-CRITICAL PARTS

All structural components will be reviewed for fracture criticality by considering those factors which govern the likelihood and consequences of their failure. The specific factors, and the criteria for assigning components or areas of components to fracture-critical status are shown in the selection logic flow chart of Figure 5-1.

5.7 DOCUMENTATION

Complete fracture analysis documentation will be maintained showing the basis for assignment of parts to fracture-critical or non-critical category, including stress states, dimensional and material characteristics, and the results of fracture analysis for each item of primary structure.



DVL = DESIGN VEHICLE LIFE FCB = FRACTURE CONTROL BOARD

Figure 5-1. Fracture-critical part selection logic.

6

REFERENCES

1. Lightweight LO_2 and LH_2 Propellant Tanks — Design Requirements, General Dynamics Convair Report No. PD 75-0044.

APPENDIX C

TEST TANK

TEST PROCEDURE

Procedure no. 64F6817
DATE 76 May 04
NO. OF PAGES 23

REPORT NO.
DATE
NO. OF PAGES

GENERAL DYNAMICS
Convair Division

Evaluation Test No. 64A6817

Test Procedure and

Test Report ☐

for

Lightweight Propellant Tank

Convair Part No. PD 75-0120

SIGNATURES

PROCEDURE	REPORT
PREPARED BY G E Copeland Test Engineer	PREPARED BY ______ Test Engineer
CHECKED BY F. K. Hilliard ETL Support Group	APPROVED BY ______ Group Engineer
APPROVED BY [illegible] ETL Support Group	CHECKED BY ______ ETL Support Group
APPROVED BY R. S. Ringwald Design Group Engineer	Witnessed by ______ Convair Inspection

REPORT SUMMARY SHEET
Acceptance Test

Part Name Lightweight Propellant Tank
Convair P/N PD75-0120
Convair S/N
IS&R 805.30.20.60

Vendor Convair
Vendor P/N N/A
Vendor S/N N/A
Security Classification Unclassified

Test	Tested Per Para. No.	Passed	Failed	Task History Reference	Data Pages	Test Dates	
						Start	Finish
Examination of Product	5.1						
Proof Pressure Test with Axial Head Load	5.2						
Engine Thrust Load	5.3						
Axial Head	5.4						
Lateral Head	5.5						

Conclusions and/or Recommendations:

Test Engineer ____________________

64A6817

NOTICES

TABLE OF CONTENTS

1.0 General Information.

1.1 Scope. This document contains the test procedures and outlines test parameters and test equipment required for the Acceptance Testing of the lightweight propellant tank described in paragraph 1.3. When all applicable testing has been completed and the requirements of Convair Report Number DDJ-66-001 have been incorporated, this document shall be the final test report.

1.2 Document Precedence. After its approval by the requesting group, the test procedure portion of this document shall take precedence over all specifications with regard to testing requirements.

1.3 Test Specimen Description. The test specimen covered by this test document is described as follows:

a. Part Name: Lightweight Propellant Tank

b. Convair Part Number: PD 75-0120

c. Vendor: Convair division of General Dynamics Corporation

1.4 Applicable Documents. Applicable portions of the following documents shall form the basis for the contents of the procedure portion of this document.

a. Convair Report Number: DDJ-66-001, "General Instructions for Component Environmental Tests".

b. Convair Drawing No: PD 75-0120 "Lightweight Propellant Tank".

c. Convair Spec. No. 0-00709, "Nitrogen - Gaseous and Liquid".

1.5 Witnessing and Certification.

a. The test engineer shall make an entry in the "Inspection Call Sheet" at the beginning of each shift during which testing is to be performed, notifying Convair Inspection as to the scheduled time and location of each test to be performed. Testing may proceed without a witness after waiting a minimum period of fifteen minutes beyond the call time.

1.0 <u>General Information.</u> (Contd)

1.5 <u>Witnessing and Certification.</u> (Contd)

b. Prior to or during testing, Convair Inspection shall complete at least one Component Test Checklist (Form A4282). The test engineer shall be furnished with the vellum originals of the checklists prepared for the test. All checklist originals, including any corrective action statements, shall be included in the final test report. The Convair Inspector shall sign the final test report certifying that the data was obtained in accordance with the test procedure.

1.6 <u>Test Specimen Identification.</u> The test specimen shall be identified as specified for Non-Destructive Testing, Para. 7.1, Convair Report No. DDJ-66-001.

2.0 *Test Facilities and Equipment:*

The test agency shall be responsible for providing the material and facilities required for performing the test in accordance with this document.

The test facilities and equipment used during the performance of this test shall be listed below. The test engineer shall complete the list.

Calibrated equipment certified to be within current calibration interval. ☐ Insp. Stamp

TYPE	MANUFACTURER	MODEL	S/N	RANGE	ACCURACY	ESL NUMBER

2.0 <u>Test Facilities and Equipment:</u> (Continued)

Calibrated equipment certified to be within current calibration interval. ☐ Insp. Stamp

TYPE	MANUFACTURER	MODEL	S/N	RANGE	ACCURACY	ESL NUMBER

3.0 Operating Requirements and Tolerances.

3.1 Pressures:

a. Design Limit Pressure

Specimen Empty	18.6 (±0.07) N/cm^2 (27.0 (±0.1) psig)
Specimen Full of Water	16.6 (±0.07) N/cm^2 (24.0 (±0.1) psig)

b. Proof Pressure

Specimen Empty	19.5 (±0.07) N/cm^2 (28.3 (±0.1) psig)
Specimen Full of Water	17.4 (±0.07) N/cm^2 (25.2 (±0.1) psig)

3.2 Leakage. Any audible gaseous leakage or visible water leakage is not allowed and should be repaired before testing is continued.

3.3 Damage. The test specimen shall show no damage or deformation during, or as a result of, any test specified in paragraph 5.0.

3.4 Test Fluid. Deionized water (D. I. H2O) shall be used as the test fluid. The test specimen may be pressurized using filtered shop air.

3.5 Test System. The test system shall be equipped with appropriate safety provisions to prevent overpressurization or evacuation of the test specimen.

4.0 Special Instructions.

4.1 Test Specimen Handling. The test specimen is a lightweight structure with a skin thickness as thin as 0.0635 cm (0.025 inches). Care should be exercised in the handling of the specimen so as not to damage the tank skin. A combination handling and test fixture will be used for supporting the test specimen. Hinges on the fixture will enable rotation of the test specimen from the vertical to the horizontal orientation. Maintain a tank pressure of 10.3 N/cm^2 (15.0 psig) during test specimen rotation. Maintain a specimen ullage pressure of 3.4 N/cm^2 (5.0 psig) during any transportation operations of the test specimen.

4.2 Test Specimen Exposure to Water. During the testing specified in paragraph 5.0, the maximum length of time that the test specimen may contain deionized water is twenty four (24) hours. If the test specimen has contained water in excess of 24 hours it should be drained and the wetted surfaces blown dry with gaseous nitrogen (GN_2) to prevent corrosion.

As soon as practical after draining water from the test specimen, the wetted surfaces should be dried with gaseous nitrogen.

In order to decrease the corrosive effects on the test specimen due to water exposure, an inhibitor (sodium dichromate - $Na_2\,Cr_2\,O_7$ - 0.1% by weight) may be added to the deionized water. The inhibitor should be dissolved in approximately 50 gallons of deionized water before it is added to the test specimen deionized water. The total solution should be thoroughly mixed in order to ensure dispersion of the inhibitor.

With the inhibitor added to the deionized water, the test specimen may remain filled with a water solution in excess of 24 hours. After the test specimen is emptied the wetted surfaces shall be washed with deionized water and blown dry with GN_2. The test fluid, with the inhibitor, can not be placed in the city sewer system. Maintenance (Dept. 250) should be contacted in order to make arrangements, through a disposal company, for the disposal of the solution.

5.0 Test Procedure.

5.1 Examination of Product. Visually examine the test specimen for any evidence of damage, deformation, excessive surface scratches, or non-conformance with specifications. Record the quality of workmanship and any discrepancies found in the test specimen.

5.2 Proof Pressure Test with Axial Head Load.

CAUTION: Because the test specimen is a thin-skinned vessel, care should be taken not to scratch or otherwise deface the tank surface. Care should be exercised not to stand or lean on the tank structure during installation of the strain gages or tank door.

a. Install internal and external strain gages as required in Figures 1 and 2. Internal strain gages should be waterproofed. Record results.

b. Install the tank doors and torque as required on Convair Dwg. PD75-0120. Record results.

c. Connect the test specimen in the test setup depicted in Figure 3, except do not connect the thrust load hydraulic cylinder. Install linear motion transducers as shown in Figure 4.

d. Record all data at zero load and zero pressure conditions.

e. Using deionized water fill the test specimen until the specimen is full.

f. Record all data with zero pressure and the test specimen full of water.

g. Using filtered shop air, slowly pressurize the test specimen to 17.4 (±0.07) N/cm^2 (25.2 (±0.1) psig) in 2.1 N/cm^2 (3.0 psig) increments. Record all data at each pressure level.

h. Maintain 17.4 (±0.07) N/cm^2 (25.2 (±0.1) psig) for a five (5) minute period. Record pressure.

i. At completion of the hold period reduce the test specimen to zero pressure.

5.0 Test Procedure. (Contd)

5.2 Proof Pressure Test with Axial Head Load. (Contd)

j. Record all data at zero pressure.

k. If testing is not to continue then drain the water from the test specimen while maintaining a positive test specimen pressure (Ref. Para. 4.2).

l. Examine the test specimen for any damage or deformation and record results.

5.3 Engine Thrust Load Test.

a. Install the test specimen in a test setup as depicted in Figure 3 and Figure 4.

b. Record all data at zero conditions.

c. If the specimen is not full of deionized water from previous testing then fill the test specimen. Record all data at zero pressure.

d. Slowly increase the test specimen pressure to 16.5 (±0.07) N/cm^2 (23.9 (±0.1) psig). Record all data. Maintain test specimen pressure at 16.5 (±0.07) N/cm^2 (23.9 (±0.1) psig) during the thrust load application. Record pressure.

e. Increase the thrust load to 51,417 N (11,560 lbs) in 10% increments. Record all data at each load increment and record peak thrust load.

f. Reduce the thrust load to zero pounds thrust and record all data.

g. Reduce the specimen to zero pressure and record all data.

h. Drain the water from the test specimen while maintaining a positive test specimen pressure.

i. Record all data with the test specimen empty and at zero pressure.

j. Examine the test specimen for any damage or deformation. Record observations.

5.0 Test Procedure. (Contd)

5.4 Axial Head Test.

a. Install the test specimen in a test setup as shown in Figure 3 and Figure 4, without the thrust cylinder attached.

b. Record all data at no load conditions.

c. Using deionized water, fill the test specimen one half full. If, due to previous testing, the test specimen is full then drain until the test specimen is one half full. Maintain a positive test specimen pressure during the draining. Record results.

d. Record all data with zero pressure and the test specimen half full.

e. Pressurize the test specimen to 17.5 (±0.07) N/cm^2 (25.4 (±0.1) psig) in 2.1 N/cm^2 (3.0 psig) increments. Record all data at each pressure level and record pressure.

f. Reduce the pressure to zero pressure.

g. After allowing sufficient time for the test specimen to temperature-stabilize, record all data outputs at zero pressure.

h. Examine the test specimen for any damage or deformation. Record observations.

i. Drain all water from the test specimen while maintaining a positive test specimen pressure. Record results.

j. Record all data with zero pressure and without water in the test specimen.

k. Pressurize the test specimen to 18.6 (±0.07) N/cm^2 (27.0 (±0.1) psig) in 2.1 N/cm^2 (3.0 psig) increments. Record pressure.

l. Record all data at each pressure level.

m. Reduce the test specimen to zero pressure and record all data.

n. Record all data with the test specimen empty and zero pressure.

o. Examine the test specimen for any damage or deformation. Record results.

5.0 Test Procedure. (Contd)

5.5 Lateral Head Test.

a. Install the test specimen in a test setup depicted in Figure 3 and Figure 4, except without the thrust load cylinder attached.

b. Record all data at zero conditions.

c. Using deionized water, fill the test specimen full and record all data at zero psig. Record results.

d. Pressurize the test specimen to 10.3 (±0.07) N/cm^2 (15.0 (±0.1) psig) and maintain pressure during the test specimen rotation. Record pressure.

e. Rotate the test specimen and support structure until the vertical axis is horizontal. Record all data.

f. Pressurize the test specimen to 18.6 (±0.07) N/cm^2 (27.0 (±0.1) psig) in 2.1 N/cm^2 (3.0 psig) increments. Record pressure.

g. Record all data at each pressure level.

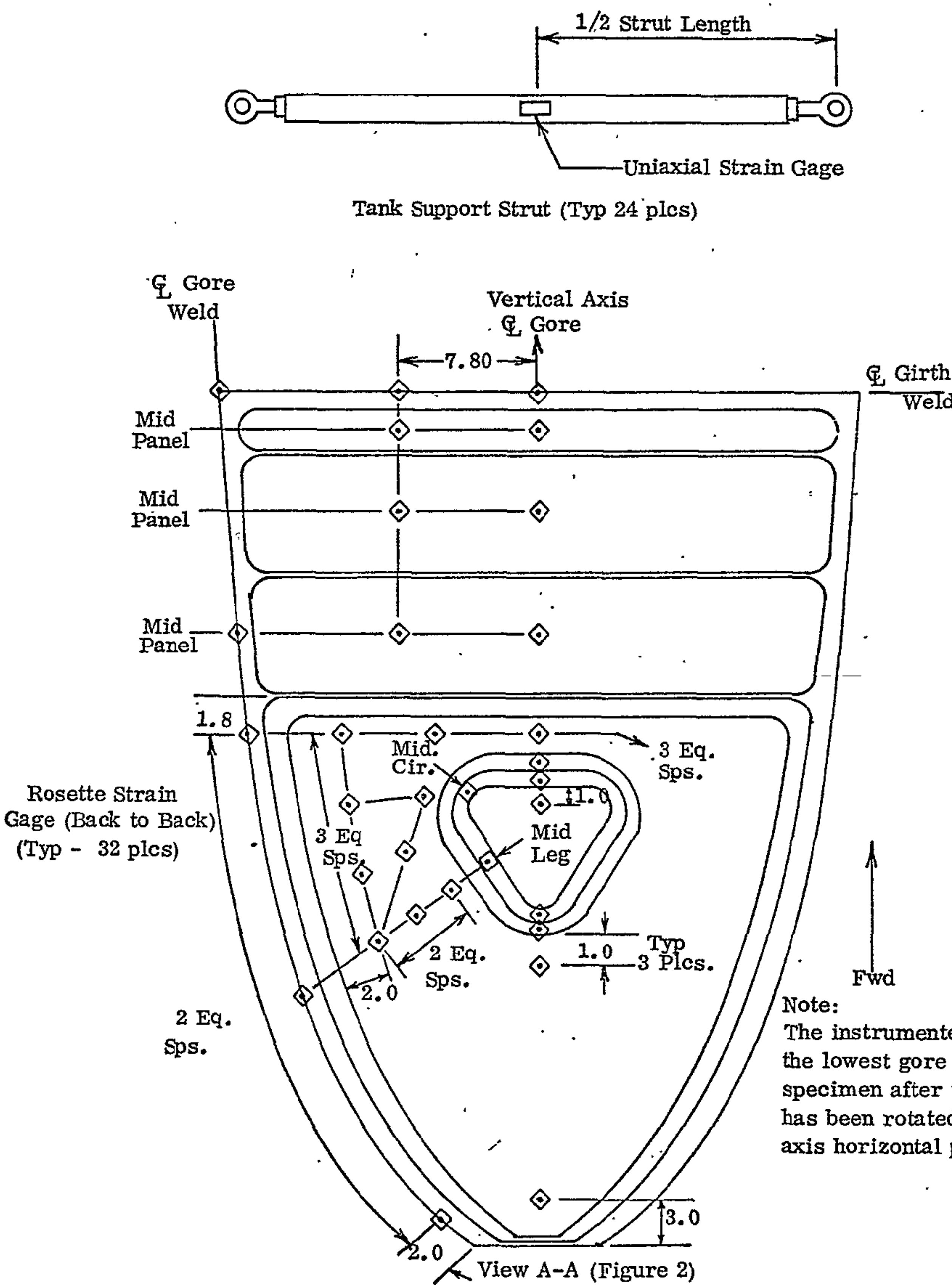
h. Reduce the test specimen pressure to 10.3 N/m^2 (15 psig), and record all data.

i. Return the test specimen to the vertical position and record all data at zero psig. Record results.

j. Drain the water from the test specimen while maintaining a positive test specimen pressure.

k. Record all data at zero pressure and with the test specimen empty.

l. Examine the test specimen for any evidence of damage or deformation. Record observations.



Note:
The instrumented gore shall be the lowest gore on the test specimen after the test specimen has been rotated to the vertical axis horizontal position.

Figure 1 — Strain Gage Locations — Tank Gore and Support Strut

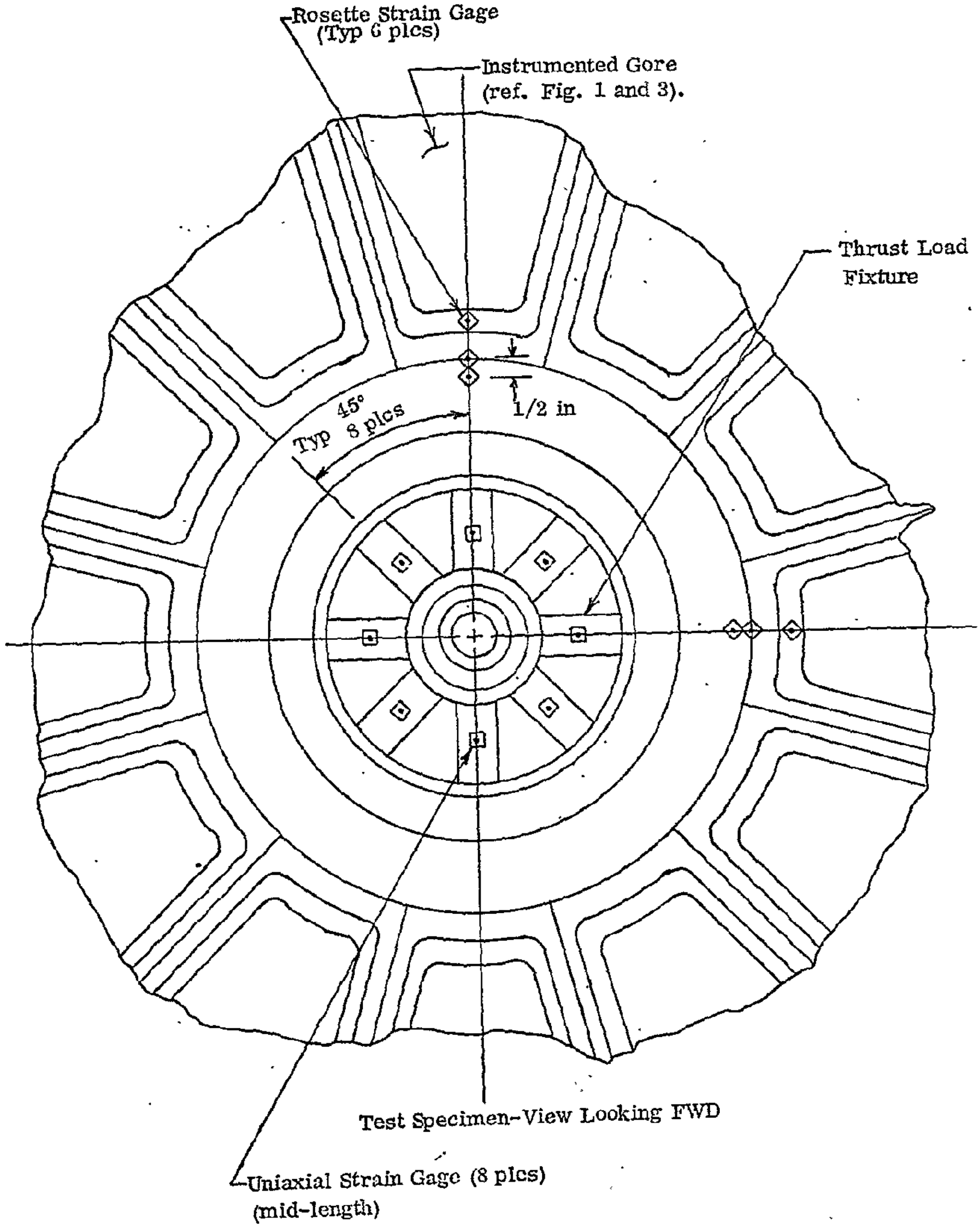


Figure 2. Strain Gage Locations — Tank Door and Thrust Load Fixture

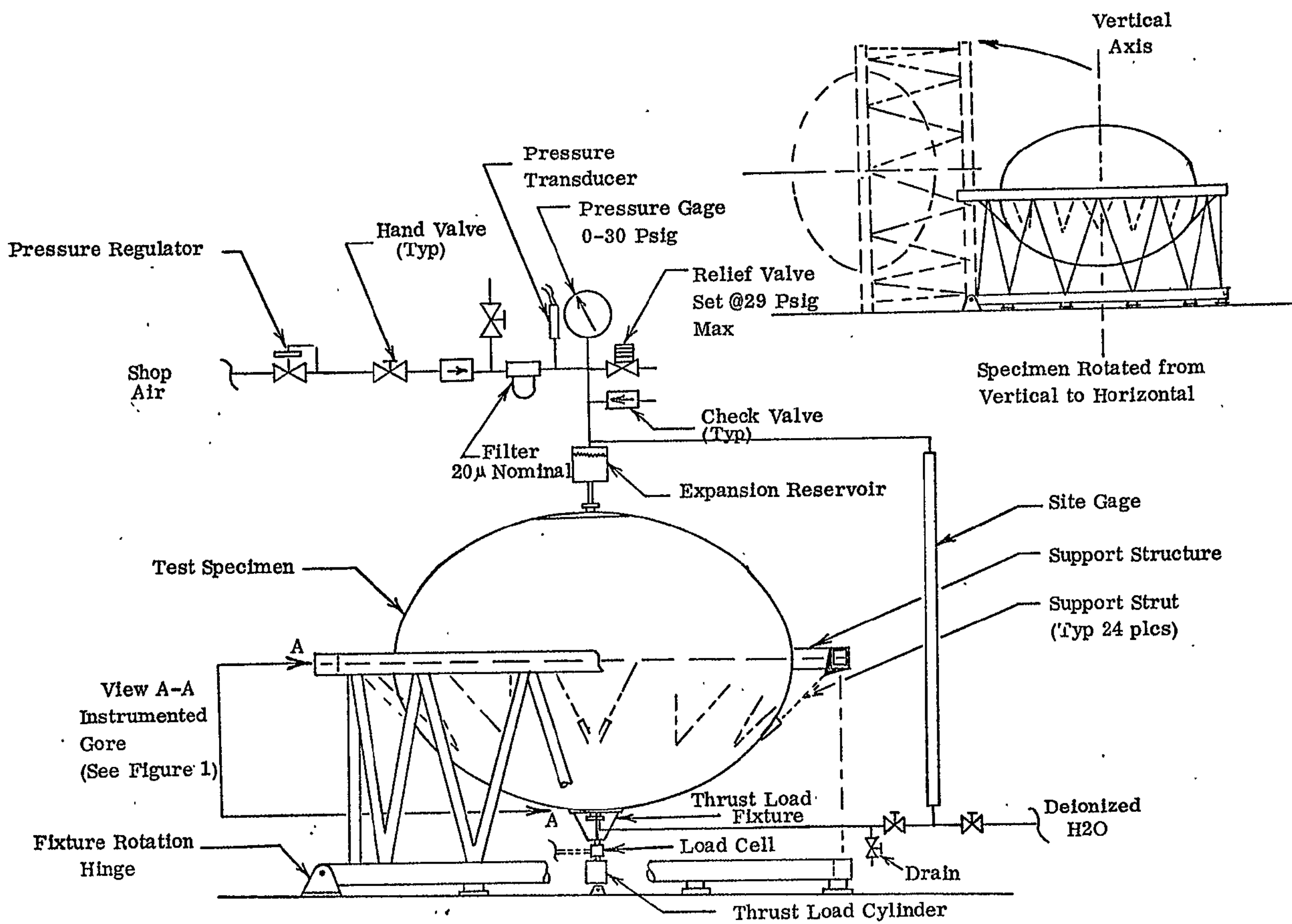


Figure 3 — Pressure Test Setup

64A6817

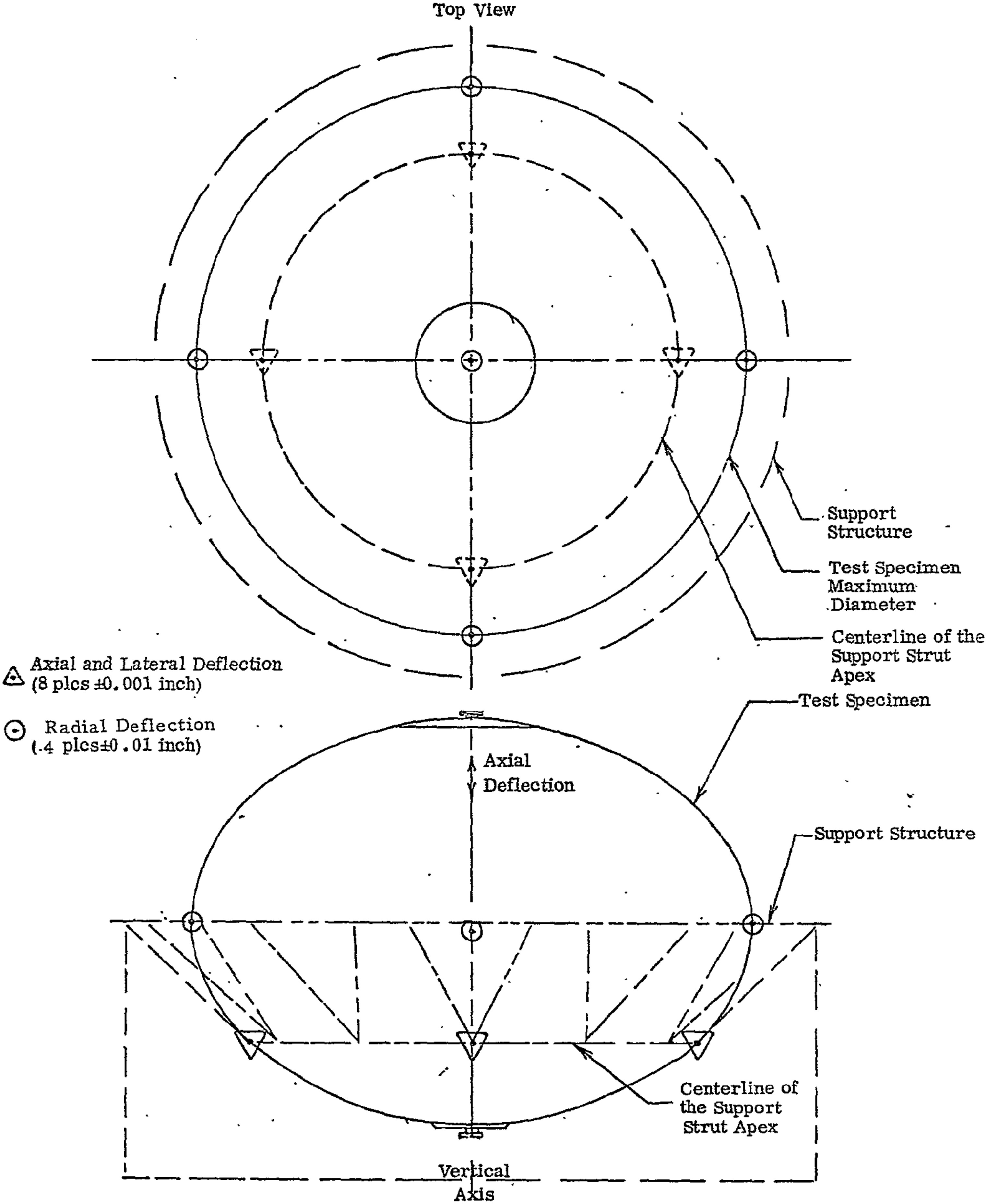


Figure 4 — Linear Motion Transducer Locations

Table I, Examination of Product (Para 5.1)

Convair P/N PD75-0120 Date ____________

Part Name Lightweight Propellant Tank

Convair S/N ____________ Test Engineer ____________

Vendor Convair

Parameter	Test Results
Workmanship	
Nameplate Data	
Surface Scratches and/or Defects	
Damage, Deformation, etc.	

Remarks:

Table II, Proof Pressure Test with Axial Head Load (Para. 5.2)

Convair P/N PD75-0120 Date

Part Name Lightweight Propellant Tank

Convair S/N Test Engineer

Vendor Convair

Para. No.	Parameter	Requirement	Results
5.2a	Strain Gages Installed	Satisfactory	
5.2b	Doors Installed and Torqued	Satisfactory	
5.2e	Test Specimen Full D.I. H2O	Full	
5.2g	Test Specimen Pressurized to 17.4(±0.07) N/cm^2 (25.2 (±0.1) psig)	17.4 N/cm^2 (25.2 psig)	
5.21	Post Proof Pressure Examination	No Damage or Deformation	

Remarks:

Table III, Engine Thrust Load Test (Para 5.3)

Convair P/N PD75-0120 Date

Part Name Lightweight Propellant Tank

Convair S/N Test Engineer

Vendor Convair

Para No.	Parameter	Requirement	Results
5.3c	Test Specimen full D.I. H_2O	Full	
5.3d	Test Specimen Pressurized to 16.5 (±0.07) N/cm^2 (23.9 (±0.1) psig)	16.5 N/cm^2 (23.9 psig)	
5.3e	Thrust Load	51,417 N (11,560 lbs)	
5.3j	Post Test Examination	No Damage or Deformation	

Remarks:

Table IV, Axial Head Test (Para 5.4)

Convair P/N PD75-0120 Date

Part Name Lightweight Propellant Tank

Convair S/N Test Engineer

Vendor Convair

Para No.	Parameter	Requirement	Results
5.4c	Test Specimen 1/2 Full D.I. $H2O$	1/2 Full	
5.4e	Test Specimen Pressurized to 17.5 (±0.07) N/cm^2 (25.4 (±0.1) psig)	17.5 N/cm^2 (25.4 psig)	
5.4h	Post Pressure Examination	No Damage or Deformation	
5.4i	Test Specimen Empty of D.I. $H2O$	Empty	
5.4k	Test Specimen Pressurized to 18.6 (±0.07) N/cm^2 (27.0 (±0.1) psig)	18.6 N/cm^2 (27.0 psig)	
5.4o	Post Pressure Test Examination	No Damage or Deformation	

Remarks:

Table V, Lateral Head Test (Para 5.5)

Convair P/N PD75-0120 Date

Part Name Lightweight Propellant Tank

Convair S/N Test Engineer

Vendor Convair

Para No.	Parameter	Requirement	Results
5.5c	Test Specimen Full D.I. H2O	Full	
5.5d	Test Specimen Pressurized to 10.3 (±0.07) N/cm^2 (15.0 (±0.1) psig)	10.3 N/cm^2 (15.0 psig)	
5.5e	Test Specimen Rotated to Horizontal Position	Horizontal	
5.5f	Test Specimen Pressurized to 18.6 (±0.07) N/cm^2 (27.0 (±0.1) psig)	18.6 N/cm^2 (27.0 psig)	
5.5h	Test Specimen Pressurized to 10.3 (±0.07) N/cm^2 (15.0 (±0.01) psig)	10.3 N/cm^2 (15.0 psig)	
5.5i	Test Specimen Rotated to Vertical	Vertical	
5.5l	Post Test Examination	No Damage or Deformation	

Remarks:

APPENDIX D

LIGHTWEIGHT PROPELLANT TANK

STRUCTURAL TEST PROGRAM

LIGHTWEIGHT PROPELLANT TANK STRUCTURAL TEST PROGRAM

INTRODUCTION

The lightweight test tank configuration represents an optimum Space Tug LO_2 tank. This configuration was developed through systematic analyses and trade studies based on definitive design requirements assembled from Space Transportation System Orbiter mission and Tug requirement studies. The selected LO_2 tank contour and support characteristics in conjunction with the selected LH_2 tank configuration resulted in the shortest Tug vehicle with the maximum payload capability.

The minimum gage used for the test tank membrane was based on the Tug LO_2 tank parametric fracture mechanics analysis. The Tug has a minimum service life of fifty missions therefore the facture mechanics analysis used 200 missions (4 times the required service life) as its criteria. The design mission profile is defined in the Lightweight LO_2 and LH_2 Propellant Tanks Design Requirements document PD75-0044. This requirements document also contains the axial and lateral design load factors. The support strut system location precludes shell buckling due to contour/pressure but the lateral load condition causes hoop compression in the membrane at and near the girth. In the LO_2 Tug tank as well as the test tank ring stiffeners have been designed into the shell to preclude shell buckling.

A structural test program has been outlined which will accomplish three objectives in three phases:

Phase I - Life Cycle test objective:

Verify the test tank capability to sustain 200 typical Tug missions.

Phase II - Hoop Compression Buckling Test objective:

1) Establish the magnitude of hoop compression loading due to propellant inertia which will buckle the wall of the test tank.
2) Produce a post buckled zone in the tank wall.
3) Establish the extent and geometry of the buckled area.

4) Produce test data which can be used to validate analytical techniques for predicting the onset of hoop compression buckling of doubly curved bulkheads due to propellant inertia loading

Phase III - Growth Characteristics of Induced Flaws Under Representative Mission Loading objective:

Determine the behavior of the test tank in the presence of induced flaws when exposed to life cycle type loads and environments.

Each phase has been defined separately so that any one or all of the tests may be performed and still accomplish the stated objectives of each.

PHASE I

LIFE CYCLE TEST

The reusability requirement of the Space Tug vehicle requires that the minimum tank membrane gage be determined through fracture mechanics analysis using stress intensity factors derived from laboratory specimen pre-flowed and tested under controlled conditions. The results of such analysis have defined the limit of acceptable flaw size versus gage. The test tank has been designed and fabricated based on a maximum flow size of .0635 cm (.025 in.) length. The tank was fabricated using production tooling and production methods. It has surface texture from chem milling, some weld porosity and weld repair which is common in aluminum tank construction. This thin walled test tank presents a unique opportunity to test a large scale production type tank.

<u>Test Objective:</u>

Verify the test tank capability to sustain 200 typical Tug missions.

<u>Test Equipment:</u>

For this series of tests the test tank and test fixture used in the design evaluation testing will be used. The tank will be filled with LN_2 to simulate cryogenic conditions.

<u>Test Instrumentation:</u>

Six additional Rosette strain gages will be installed at weld repair locations as determined from radiographic records.

<u>Test Procedures:</u>

The fill and pressurization procedure shall follow the typical mission profile shown in figure 1.

1) Initial detailed tank inspection and documentation x-ray and dye penetrant of welds
2) Fifty mission cycles shall be performed as defined in figure 1.
3) A complete review of all test data
4) Fifty additional mission cycles shall be performed

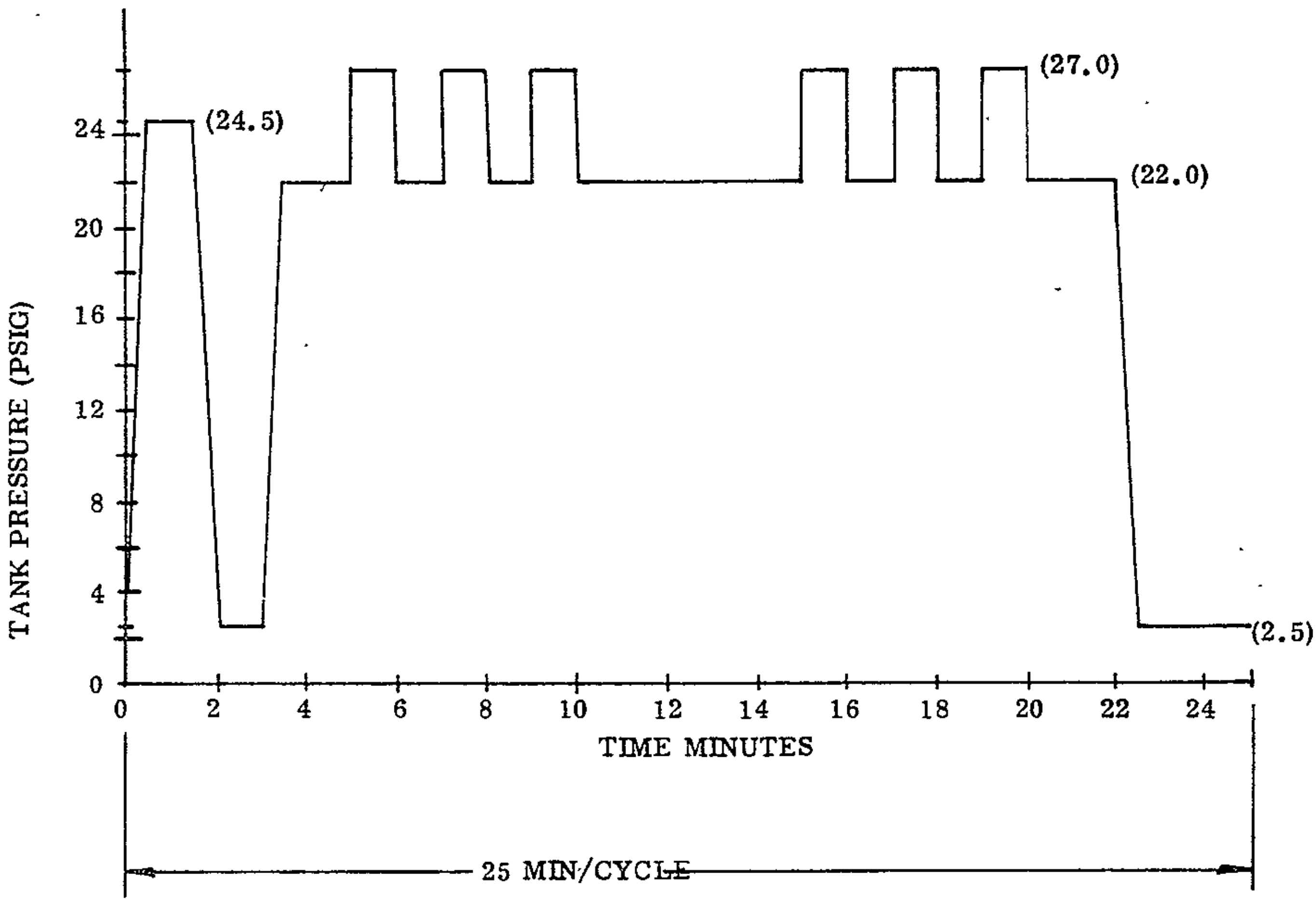


Figure 1. Proposed Test Tank Pressure Profile (1 Cycle).

5) A complete review of all test data plus a detailed tank inspection *

6) Fifty additional mission cycles shall be performed

7) A complete review of all test data

8) Fifty additional mission cycles shall be performed

9) A complete review of all test data plus a detailed tank inspection*

*Note: LN_2 boil-off rate is estimated at 600 lbs per hour. Tank volume is approximately 375 cubic feet.

Report

Define the test setup and all test instrumentation. Present the systematic test results. Identify all flaw changes. Discuss results of the test with respect to the tank design criteria. Determine the tank acceptability for the next phase of testing.

PHASE II

HOOP COMPRESSION BUCKLING TEST

Lightweight propellant tanks of space vehicles such as the space tug experience high axial and lateral accelerations during space shuttle operations. These accelerations produce propellant inertia loading which, depending on ullage pressure, tank geometry, and propellant level, can induce zones of high hoop compression loading in the tank wall.

Analytical methods have been developed to accurately predict the magnitude of this hoop compression loading. However, relatively little analysis or testing has been performed to establish the allowable hoop compression loading (i.e., hoop compression buckling allowable) due to propellant inertia. This hoop compression buckling allowable data is particularly sparce for lateral inertia effects on doubly curved bulkheads.

For the lightweight test tank design integral stiffening, increased tank wall thickness and ullage pressure control were used to ensure the tank would not buckle due to hoop compression side loading. This approach was selected to ensure the tank would not be damaged during the test program. Therefore, although the test results can be used to verify the magnitude of hoop compression loading predicted analytically, the tank evaluation test will not establish the hoop compression load at which buckling occurs.

Buckling Test Objectives

1) Establish the magnitude of hoop compression loading due to propellant inertia which will buckle the wall of the test tank.

2) Produce a post-buckled zone in the tank wall. The area of the post-buckled zone will be maximized within the constraints of the test set-up.

3) Establish the extent and geometry of the buckled area.

4) Produce test data which can be used to validate analytical techniques for predicting the onset of hoop compression buckling of doubly curved bulkheads due to propellant inertia loading

Test Equipment

For this series of tests the test tank and test fixture used in the design evaluation tests will be used. The test tank will be filled with water.

Test Instrumentation

Use design evaluation test instrumentation plus added instrumentation (strain gages) installed near girth of test tank. (24 rosette strain gages would be added for this test).

Test Procedure

Place tank in horizontal position with tank filled with water. Start with minimum ullage pressure established for tank evaluation test with tank in horizontal position. Incrementally reduce ullage pressure to 0 psi. Measure strains and deflections at each increment. Visually examine for buckling. Record buckle depths and buckle patterns.

Report

Define the test setup and all test instrumentation. Present the systematic test results. Identify the buckle pattern and location. Discuss the results of the test with respect to the tank design criteria. Determine the tank acceptability for the next phase of testing.

PHASE III

GROWTH CHARACTERISTICS OF INDUCED FLAWS UNDER REPRESENTATIVE MISSION LOADING

This test is similar to the phase I test series except that flaws are induced similar to the flaws induced in laboratory specimen. These flaws will therefore represent the flaws which were used to establish the stress intensity factors used in fracture mechanics analysis.

Objective:

Determine the behavior of the tank in the presence of induced flaws when exposed to life cycle type loads and environments. Other objectives include determination of crack growth rates and sensitivities in various areas of the tank.

Approach:

The general test loading plan is similar to that of Phase I, i.e., apply loads and environments to the pressure vessel that approximate the expected service of the structure.

In this phase, however, the tank will be intentionally damaged by inducing carefully controlled flaws in the tank walls. Since the fracture mode of this pressure vessel is leak-before-break, a part through flaw should propagate through the thickness of the tank wall before fracture will occur. In such a case, the testing will be stopped when a leak of the internal fluid is detected.

It is proposed that multiple flaws be induced in the tank in several locations in such a manner that the predicted leak cycle will be the same (theoretically). This requires knowledge of the local stresses and the crack characteristics of the material in the as-used conditions.

The flaws will be induced in four locations that are accessible to inspection and these locations will include both the parent metal and weldments. If possible, it is desirable that one of the flaws be induced on the inside wall of the tank. In this case the

outside surface of the tank can be inspected visually for signs of crack breakthrough. It should be possible to determine when the leading edge of the crack is within one plastic zone of the outside surface by detection of the visible plastic deformation.

Other flaw growth will be measured periodically using nondestructive testing methods.

Flaws

Flaws for the parent material will be machined into the surface of the skin by either mechanical methods or by a portable electrical discharge machine. The same method could be used for the weldments.

However, there are several possible ways to induce flaws in the weldments that more closely simulate "natural" flaws. For example, a series of tiny holes can be drilled in a given weldment followed by a partial penetration weld pass, Convair has been successful in inducing flaws by this method that resemble gross porosity or inclusions

A second method (also used successfully) calls for machining (gouging) out a portion of the weld, insertion of thin tungsten flakes, and refilling of the gouged out region with weld filler, (manual weld repair). This results in some lack of fusion areas that have a predetermined shape and location.

The weld flaws described in these two examples provide imbedded flaws that are common in fabricated structures but are not usually used for standard fracture testing.

Test Equipment

Same as Phase I.

Test Instrumentation

Same as Phase I except add strain gages in locations of induced flaws.

Test Procedure

Same as Phase I.

Report

Same as Phase I.